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**MONTEREY, CALIFORNIA**

## **THESIS**

**DESIGN OF A PREMIXED GASEOUS ROCKET ENGINE  
INJECTOR FOR ETHYLENE AND OXYGEN**

by

David F. Dausen

December 2006

Thesis Advisor:  
Second Reader:

Christopher M. Brophy  
Jose O. Sinibaldi

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**DESIGN OF A PREMIXED GASEOUS ROCKET ENGINE INJECTOR FOR  
ETHYLENE AND OXYGEN**

David F. Dausen  
Lieutenant, United States Navy  
B.S., United States Naval Academy, 1998

Submitted in partial fulfillment of the  
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**NAVAL POSTGRADUATE SCHOOL  
December 2006**

Author: David F. Dausen

Approved by: Christopher M. Brophy  
Thesis Advisor

Jose O. Sinibaldi  
Second Reader

Anthony J. Healey  
Chairman, Department of Mechanical and Astronautical  
Engineering

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## **ABSTRACT**

A premixed gaseous rocket injector was designed and successfully operated over a limited range of fuel-rich operating conditions for the purpose of soot modeling for ethylene and oxygen mixtures. The injector had the advantage of delivering a homogenous mixture to the combustion chamber, lower soot production, and higher performance potential by removing the fuel atomization process which affects the combustion process and is inherent for non-premixed injectors. The premixed injector was operated at oxygen-fuel ratios from 1.0 to 1.8 with a mass flow of 0.024 kg/sec achieving a chamber pressure of 76 psi without propensity of flashback for 0.032" injector orifices. Increased mass flow rates of 0.027 kg/sec were achieved by increasing the injector orifice diameters to 0.0625" which produced a chamber pressure of 127 psi and a characteristic exhaust velocity efficiency of 90.1 %. Flashback was eventually observed at an oxygen-to-fuel ratio of 1.2 where the pressure drop was across the injector was less than 388.6 kPa and the bulk mixture velocity through the injector orifices was approximately 90 m/s. Maintaining bulk velocity sufficiently above this value should prevent flashback from occurring, but will likely need to be characterized for additional orifice diameters and pressure differentials.

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## I. INTRODUCTION

Conventional gaseous rocket engines inject the fuel and oxidizer separately into the combustions chamber where the reactants mix locally and combust. Ideally the fuel and oxidizer should be fully mixed prior to combustion to achieve the highest combustion efficiency for the propellants. This can be achieved by premixing the reactants and then injecting the mixture into the combustion chamber. Mixing delays will be nearly eliminated allowing a much quicker and uniform combustion zone. An engine will benefit by having a greater characteristic exhaust velocity efficiency ( $\eta_{c*}$ ), less soot production and possibly fewer instability modes. Though the benefits of this concept are apparent, practical operation has been difficult to achieve due to a combustion phenomenon known as flashback. Flashback is the upstream propagation of a flame front into the premixing manifold and often occurs when the gas velocity exiting the injector is less than the flame velocity of the premixed propellants. If the flame velocity is higher than the propellant velocity through the injector ports, the flame travels upstream through the injector into the mixing chamber which has the potential to damage hardware and possibly detonate the mixture. A properly designed injector must insure the premixed gaseous velocity must be significantly greater than the flame velocity to provide a stability margin during operation.

Designing a successful premixed injector is a challenging endeavor. There two fundamental parameters to insure the injector is able to support stable combustion; an aerodynamic approach and quenching. An aerodynamic approach insures the injector introduces the propellants at a velocity at a margin above the flame velocity of propellants, thus keeping the flame front away from the injector ports. Flame quenching is another approach at which the injector is able to extinguish the flame by local heat transfer. Flame quenching is the method of producing injector orifices smaller than the quenching diameter of the reactants. The flame is prevented from flashing back even though the velocity of the reactants may not be higher than the flame velocity by removing heat from the flame along the burner rim restricting it from traveling upstream and detonating the reactants in the mixing chamber. Using the aerodynamic approach, small diameter injector orifices will ensure the velocity remains high, but attention must

be made to the slower moving boundary layer against the injector walls. A smooth injector wall will insure the boundary layers will remain thin and it is also critical the injector is cooled to quench a flame which may propagate upstream via the boundary layer and is extremely important for longer run durations.

The motivations for designing a premixed injector were to remove conventional injector effects such as atomization and mixing, thereby isolating soot production mechanisms to improve modeling efforts on the formation of soot particles in rocket plumes. Conventional hydrocarbon fuels such as RP-1 and oxygen do not combust as a homogenous mixture due to the RP-1 often being injected as a supercritical liquid. The non-ideal injection process often produces excessive amounts of carbon soot. The formation of soot is not well understood and inherently a non-equilibrium process. Droplets formed during atomization are heated prior to combustion. The lighter hydrocarbon fuel vapors are produced and consumed first by the combustion process. Near the end of the droplet heating period, only very heavy carbon-rich reactants remain which result in the production of soot particles.<sup>8</sup> By premixing gaseous ethylene and oxygen, complete mixing of the mixture prior to combustion can be achieved resulting in the soot production being dependant primarily on the chemistry associated with the given mixture ratio. The soot concentration can be correlated to the  $c^*$  efficiency of the engine since any extra soot produced above what equilibrium chemistry predicts, results in less carbon dioxide and carbon monoxide produced. The characteristic velocity,  $c^*$ , directly correlates to propellant combustion properties, combustion chamber design, and nozzle throat area.

Premixed injector designs allow homogenous mixtures to be delivered to combustion chambers and assist researchers by isolating chemistry during the combustion process from the other processes which often occur in practical systems. It is anticipated that the result will be better understanding and improved accuracy of soot production models.

## II. BACKGROUND

### A. DEVELOPMENT

The research performed in this thesis was initiated by the sponsor Sierra Engineering in support of their efforts on the contract “PERCORP Enhancement for Improved Soot Modeling”. The objective of the PERCORP (rocket PERFORMANCE CORrelation Program) Enhancement was to improve the accuracy for plume signature generation by incorporating state-of-the-art soot modeling.<sup>1</sup> PERCORP is utilized directly with Chemkin, a finite rate chemical reaction code created by Reaction Design which is used to predict the concentrations of combustion species over time. The validation of the computer models lies in hot fire test data performed at the Naval Postgraduate School.<sup>1</sup>

Sierra Engineering designed and analyzed the test hardware of a premixed injector for this project. The engine had a chamber upstream of the injector plate where the propellants were fully mixed prior to being injected into the combustion chamber. The propellants chosen for this engine were ethylene ( $C_2H_4$ ) and oxygen ( $O_2$ ). The propellants were swirled into the chamber through separate ports and then through a bead field to fully scramble the propellants and create a uniform mixture and directed flow prior to the injector or orifice plate. Following the injector plate the combustion chamber was attached along with the nozzle. The schematic and picture of the hardware are presented in Figure 1.

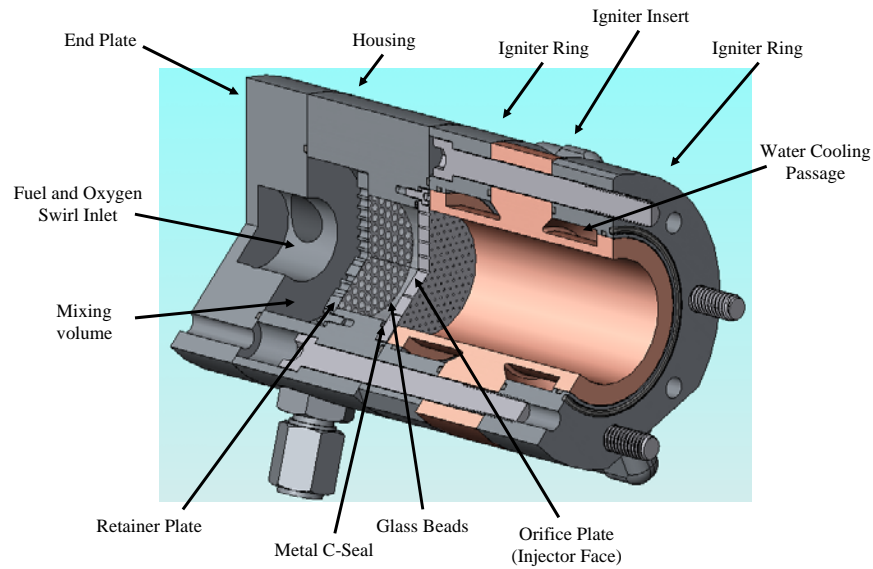


Figure 1. Sierra Engineering Original Premixed Injector<sup>1</sup>



Figure 2. Sierra Engineering Machined Premixed Injector components<sup>1</sup>

The Hot fire testing of this engine proved to be unsuccessful and various theories were presented and discussed on why these engines failed. The challenge remained to design a successful premixed injector to continue this program and understand the characteristics of premixed injectors.

## B. COMBUSTION

The flame propagation phenomenon in premixed gases is the governing mechanism for successful operation of premixed injectors and needs to be discussed and understood. Due to the presence of premixed reactants upstream of the injector plate, it is critical the gaseous velocity of the propellants in the individual injector ports must be greater than the flame velocity to maintain flame stability. The propellants chosen for this thesis were Ethylene ( $C_2H_4$ ) and Oxygen ( $O_2$ ) and the flame speeds of the premixed gases must correctly characterized to properly design the premixed injector. The Flat Flame Burner Method attributed by Powling was used to determine the laminar flame velocities.<sup>2</sup> The simple apparatus is shown below.

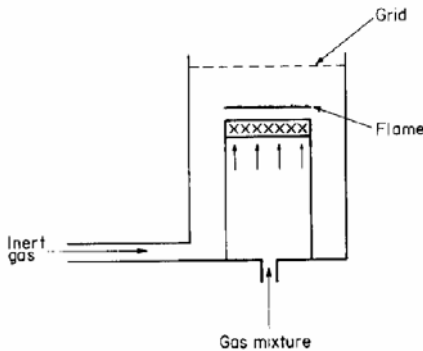


Figure 3. Flat Flame burner apparatus to measure laminar flame velocities<sup>2</sup>

The flat flame burner provides the most simple flame front where the flame can be studied accurately using visual means originally developed by Powling. The gas mixture is injected into the base of a larger diameter tube which forced to flow through a porous metal disk or small tubes of 1 mm holes or less. This is the best conditions for studying flat flames. The procedure is to ignite the flame with a high flow rate and either the mixture ratio or the flow is adjusted until the flame is flat. The diameter of the flame is measured and the area divided into the volumetric flow rate of the gaseous propellants. If the velocity of the gases are greater than the flame speed, a cone is produced due to the larger flame required. If the velocity of the gases is too slow, the flame tends to flashback and is quenched by the porous plate. The inert gas is passed around the burner

to help define the edges of the flame and a grid is placed at the exit of the burner to control the rate of efflux of burned gases. This schematic, as shown, is only practicable for gases with burning velocities of 15 cm/s or less. The research by Spalding and Botha was modified for higher flame speeds by cooling the plug. The cooling draws the flame front closer to the plug and stabilizes the flame.<sup>2</sup>

The laminar flame speeds versus equivalence ratio is given in Figure 4 below.

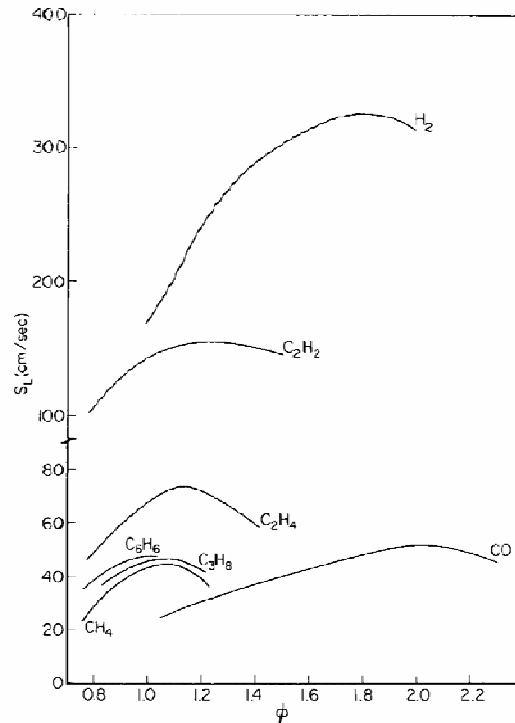


Figure 4. Laminar Flame Velocities Versus Equivalence ratio for various fuel-air mixtures at standard conditions<sup>2</sup>

The laminar flame velocities for ethylene/air are approximately 75 cm/s. This is a moderate flame velocity as compared to the flame speed of hydrogen/air at over 300 cm/s. The table of ethylene and air are found in the appendix of Glassman and are shown below.

$\Phi$	OF	Laminar Flame velocity	
		(cm/s)	(m/s)
0.80	4.28	37	0.37
0.90	3.80	50	0.5
1.00	3.42	60	0.6
1.10	3.11	68	0.68
1.20	2.85	73	0.73
1.30	2.63	72	0.72
1.40	2.44	66.5	0.665
<u>Maximum Velocity</u>			
1.13	3.03	73.5	0.735

Table 1. Laminar Flame Velocities for Ethylene and Air<sup>2</sup>

The laminar flame velocities stated in Figure 4 are for laminar flames, but the premixed injector will likely possess a turbulent flow field and therefore turbulent flame speeds should be used. It is acceptable in practice to use the laminar flame speed and increase the value by a factor of 10 to approximate the turbulent speeds. This was the initial approach. The calculated flame velocities shown in Figure 5 are from Chemkin's PREMIX module using ethylene and oxygen at ambient temperature of 70 degrees F and combustion pressure of 400. This was a more accurate baseline flame velocity from which to work with.

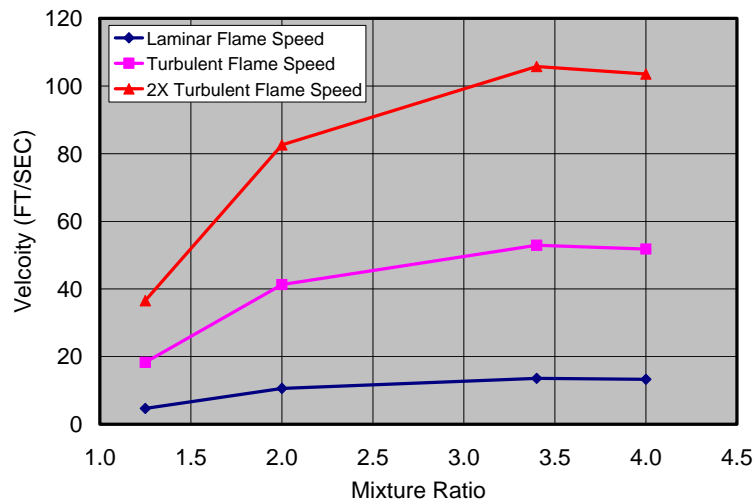


Figure 5. Laminar Flame Velocities Versus Mixture ratio for Ethylene-Oxygen<sup>1</sup>

### C. FLASHBACK AND BLOWOFF

Flame stabilization is an important condition of the combustion process.<sup>2</sup> The combustion tests to determine the laminar flame speeds discussed in the previous section require cold premixed gases to be flowing in a direction opposite of the combustion wave propagation and at a velocity equal to the propagation velocity. Therefore the wave becomes stationary with respect to the tube.<sup>2</sup> The flame would be classified as having neutral stability; but the actual flame front shifts during combustion. If the velocities of the gases are increased the flame would leave the burner surface where a portion of the flame front would fix itself to the exit. These burners are designed so the propellants are fully mixed becoming a homogenous mixture prior to combustion. The burner itself acts as a heat and combustion radical sink to stabilize the flame.

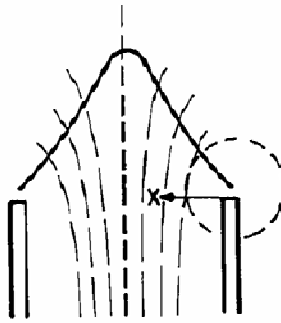


Figure 6. Streamlines from a Bunsen Burner flame<sup>2</sup>

It is important to pay attention to the boundary layer at higher gas velocities. The combustion wave does not behave as a neutrally stable flame. When the velocity of the gases is greater than the flame speed of the mixture the flame becomes conical. The greater the flow velocity of the mixture, the smaller the cone angle will become. This angle decreases so the velocity component of the flow normal to the flame is equal to the flame speed. This is due to the boundary layer affecting the flow velocity. The flow velocity is a maximum in the center of the burner, but towards the burner rim the velocity is lower and at some point the flow velocity is equal to the flame velocity. This is the point at which the flame is anchored. The flame is close to the burner rim and the stability of the flame is controlled by heat and radical loss to the wall of the burner. As the gas velocity is increased the flame will move away from the burner wall. As the



flame edge moves away from the wall the mixture become entrained with the outside air, the mixture become diluted, decreasing the flame speed until it reaches the blowoff limit. This is condition where the velocity of the flow is much greater than the flame velocity can support and combustion will not be maintained. If the gas velocity is reduced, where it is less than the flame velocity at some point on the flame it will travel upstream. The flame will propagate into the burner and will ignite the partially mixed reactants. This phenomenon is known as flashback. Figure 7 demonstrates the relationship between the premixed gaseous velocity and the flame velocity.

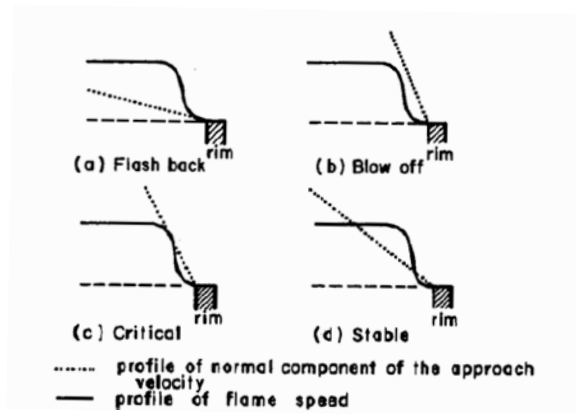


Figure 7. The Premixed Gaseous Velocity and the Flame Velocity above the Bunsen Burner rim<sup>3</sup>

An indication of when flashback is about to occur is when the flame becomes tilted as shown in Figure 8. The flame tilts because of the backpressure of the flame causing a disturbance in the flow and where the flow velocity is reduced the flame front travels upstream and flashback occurs.

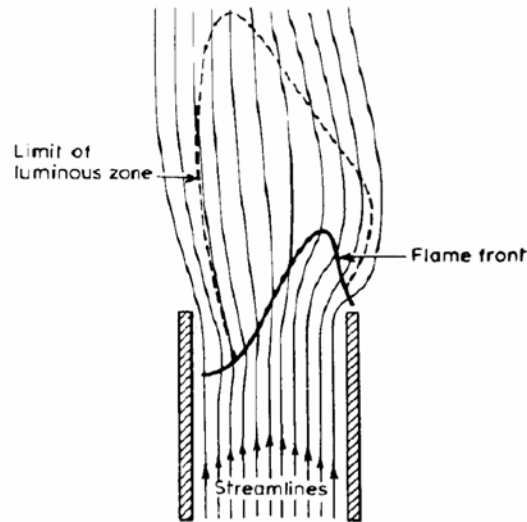


Figure 8. Tilted flame which is indicative of flashback<sup>2</sup>

An improved understanding of this behavior can be obtained by discussing the role of boundary layers in this situation. By assuming Poiseuille flow in the burner tube which is laminar, the gas velocity achieves a maximum in the center of the stream and zero velocity at the walls. Boundary layers are assumed to typically be very thin in nature, usually on the magnitude of one millimeter. This is small in comparison of the diameter of the burner. Therefore the gas velocity near the wall can be represented by an approximately linear vector profile. The flow lines are parallel with the tube and the combustion wave is formed in the stream and the edge of the wave closely approaches the burner rim. Towards this edge the burning velocity decreases as heat and chain carriers are lost to the rim of the burner. If this wave is too close to the rim the flame velocity is less than the gas velocity, therefore the wave is driven upstream of the flow. Eventually as the flame velocity decreases as heat is lost to the burner rim, the flame velocity is equal to the gas velocity. At this point the wave has reached equilibrium and becomes stationary in respect to the burner.<sup>2</sup>

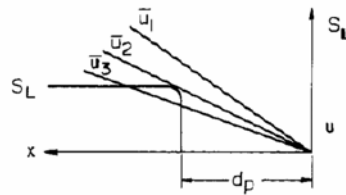


Figure 9. The Premixed Gaseous velocity and the Flame velocity just inside the Bunsen Burner rim<sup>4</sup>

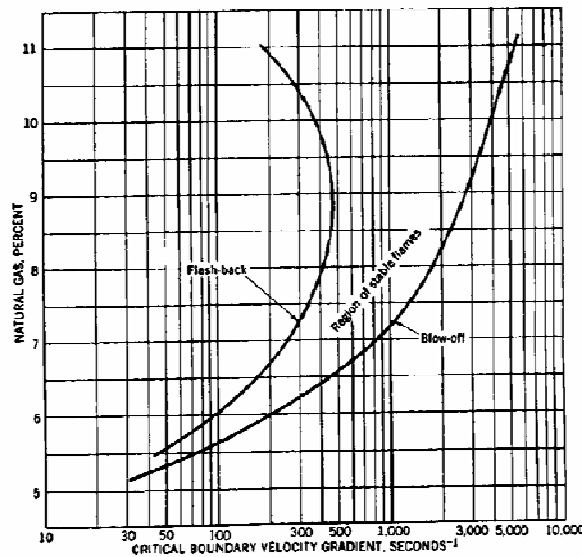


Figure 10. Flame Stability diagram for Natural gas-Air mixture<sup>4</sup>

Figure 10 is a flame stability diagram of a natural gas and air mixture. This diagram explains the behavior of the propellants characterizes the regions of flashback and blowoff. The region between these two curves bound a stable flame. Except when the tube diameter and quenching distance are of comparable magnitude then this defines extinction where flashback and blowoff intersect. This flame stability diagram requires the percent mixture of the premixed propellants and the critical boundary velocity gradient. The critical boundary velocity gradient defines the physical parameters of the injector. The velocity gradient may be used to predict the stability of the flame, and is defined by Equation 1.

$$G = \frac{4V}{\pi r^3}$$

$G$  = Boundary layer gradient (1/s)  
 $V$  = Volumetric flow (m<sup>3</sup>/s)  
 $r$  = Radius of Orifice (m)

(1)

Figure 11 shows a series of flame stability diagrams depicting the effects of varying tube diameter. Smaller tube diameters, such as 0.315 cm tubes, demonstrate the stable flame is bounded by extinction and blowoff. Flashback is not reflected in this plot since the tube diameter is equal to the smallest quenching distance of the propellants. As the tube diameter increases, extinction wanes and the stable flame is bounded by a narrow region between flashback and blowoff. It is also possible to bridge the extinction region and obtain flashback by strongly heating the burner rim. The opposite is true as well, by cooling the burner rim or injector face flashback can be prevented and the flame will remain as a stable flame. This approach was also applied to the premixed injector design.

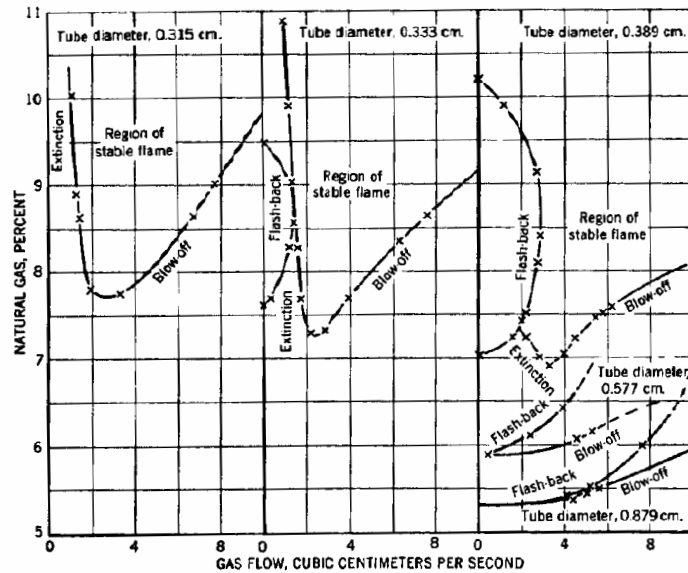


Figure 11. Regions of stable Natural gas-Air flames for several cylindrical tubes at small flows<sup>4</sup>

### III. DESIGN

#### A. SIERRA ENGINEERING PREMIXED INJECTOR

The previous premixed injector designed by Sierra Engineering was instrumental in learning the challenges of designing a premixed injector. The design requirements for the engine are to provide a wide range of combustion pressure, temperature and mixture ratio conditions. The initial decision in this program was to choose a propellant that would meet these combustion requirements and involved the consideration of several hydrocarbon fuels including Methane ( $\text{CH}_4$ ), Acetylene ( $\text{C}_2\text{H}_2$ ), Ethylene ( $\text{C}_2\text{H}_4$ ), Ethane ( $\text{C}_2\text{H}_6$ ), and Propane ( $\text{C}_3\text{H}_8$ ). Ethylene was selected since the critical temperature is often well below room temperature and would remain gaseous during most delivery conditions. The saturation points of the various fuels which were considered were shown in Figure 12. Ethylene is also known to produce comparable amounts of soot as other long-chain hydrocarbon fuels.<sup>1</sup> Gaseous oxygen was chosen as the oxidizer for this engine.

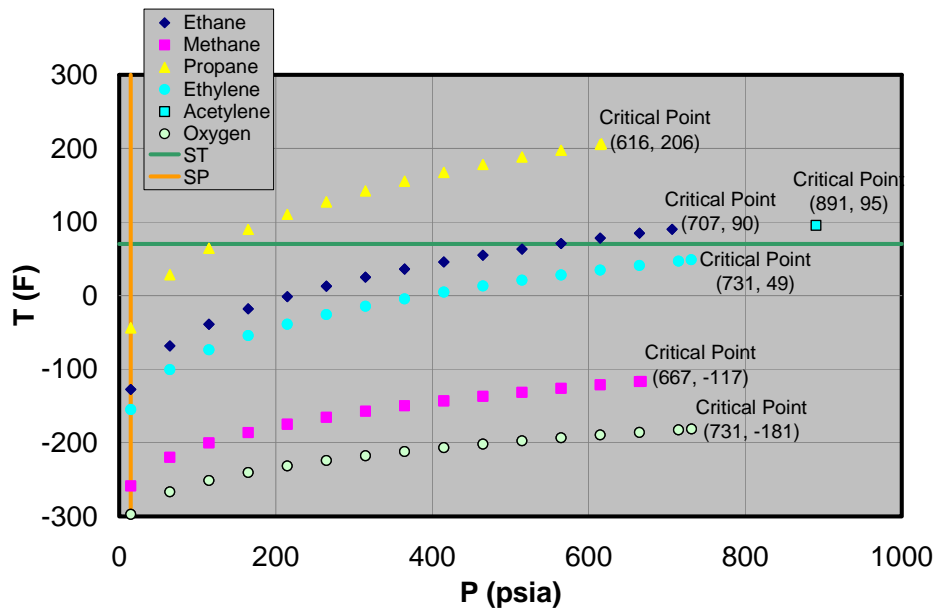


Figure 12. Saturation Points of various fuels<sup>1</sup>

An additional important parameter to consider when selecting a propellant is the laminar flame velocity of the mixtures. It is critical the gaseous velocities of the propellants are greater than the flame speed of the propellants. The propagation speeds

of the premixed laminar flames were computed using Chemkin's PREMIX module (Flame Speed Reactor).<sup>1</sup> The gases are assumed to be at ambient temperatures (70 degrees F) and a combustion chamber of 400 psi. The turbulent flame speeds were calculated using a factor of 3.9 defined by Kuo, in *Principles of Combustion*. The figure below shows the flame velocity of ethylene and oxygen.

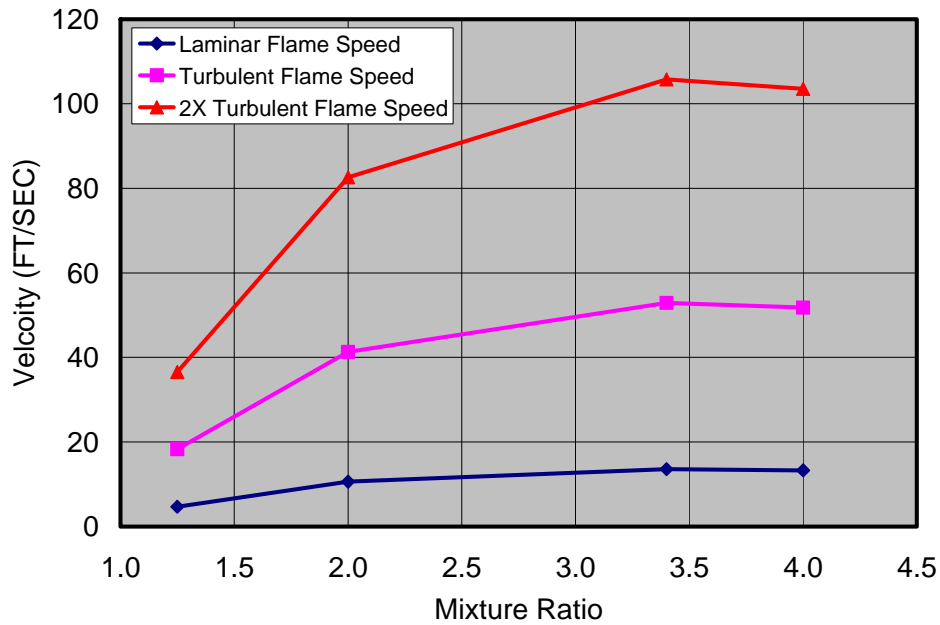


Figure 13. Ethylene/Oxygen Flame Velocities<sup>1</sup>

The injector or orifice plate was designed with the intention of maintaining the gaseous velocity higher than the maximum flame speed expected and also limiting the pressure drop across the injector to 15%. There were 199 – 0.028 inch diameter orifice holes which comprised the injector plate. The orifice holes were designed to maintain the mixture velocity through the orifice holes at least twice the turbulent flame speed.<sup>1</sup> The plate thickness was sized as 0.175 inches to limit the pressure drop across the injector. This flow is essentially a bulk flow with 199 holes filling the 1.5 diameter combustion chamber. The orifice plate was constructed of Inconel stainless steel which was intended to resist the higher combustion temperatures.

The propellant gases were introduced into the premixed chamber in an effort to fully mix the propellants prior to injection into the combustion chamber. The propellants are first introduced into the engine in a swirling fashion and then passed through a one inch bead field of 3 mm glass beads. This was an effort to mix the propellants upstream of the injector plate.

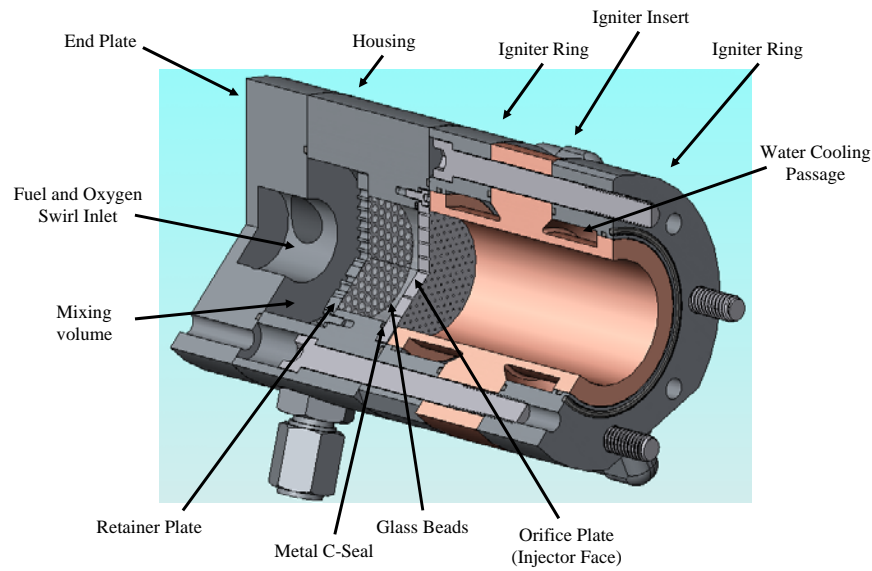


Figure 14. Sierra Engineering Original Premixed Injector<sup>1</sup>

Downstream of the three inch combustion chamber a bolt-on conical nozzle was attached. This nozzle had a throat diameter of 0.3 inches and exit diameter of 0.675 inches. The nozzle area ratio,  $\epsilon$  was 5.0625 with a nozzle total angle of 20.56 deg.

The propellants were injected into the engine for the initial test at an Oxygen to Fuel Ratio (OF ratio) of 0.91 and total mass flow rate of 0.188 lb/sec. The lower OF ratio was tested to ensure the flame velocity was low as well as the combustion temperature. The engine ignited with a lot of visible soot in the plume. Very shortly thereafter the burst disk blew denoting a pressure in the premixed chamber greater than 619 psi. The injector was significantly damaged in test as well, and is shown in Figure 15.



Figure 15. Premixed Injector following first test showing the burst disk blown with hardware loss

Figure 16 shows the bead field following the test. The view is from the upstream side where it is evident the combustion melted the bead field into a molten mass and the stainless steel retaining plate was almost completely consumed.



Figure 16. Premixed Injector showing the damage upstream of glass bead field



Figure 17 shows the orifice plate following the test, and is seen from the downstream side where the Inconel orifice plate was somewhat intact with pitting and glass material protruding from the orifice holes.



Figure 17. Premixed Injector showing the damage downstream of glass bead field and the orifice plate

It was apparent after the post test review the combustion flame traveled upstream in the form of flashback. The glass material protruding through the orifice holes indicated the combustion melted the bead field and blocked the flow path through the injector plate. The beads melted into a mass of glass blocking the flow and vaporizing the hardware to the burst disk.

On the first test the glass beads were indeed blocking the flow between the retainer and injector orifice plate. These 3 mm glass beads were placed in a random fashion into this recess to create a bead field, but the angle between radius centers of the individual glass bead and of the orifice holes were parallel to the flow resulting in blockage of the flow path.

Further analysis demonstrated the startup sequence was also flawed placing undue stress on the engine. The startup sequence was designed for a liquid rocket engine run on RP-1 and Oxygen. The sequence which occurred is shown below.

1. The engine was purged with nitrogen.
2. Oxygen flow was started as the flow of nitrogen was shut off.
3. Ethylene flow was started simultaneously with the hydrogen/oxygen torch.

This sequence is initiated with oxygen where the fuel is injected simultaneously with the torch. The combustion starts out with relatively high OF ratio and is then reduced. This start was too hard for this injector and may have contributed to the failure due to the high reactivity and flame velocities at the brief but near stoichiometric mixtures.

After the start sequence was reviewed, the start was 'softened' to ensure the engine did not undergo any undue stress on starting. The sequence was changed to lead with fuel and then the oxygen was introduced into the flow as the torch was initiated. The oxygen was also diluted with nitrogen to ramp up the oxygen as the torch is turned on. The nitrogen was turned off simultaneously with the torch. This allowed the engine to start the combustion fuel rich and progress to the desired OF ratio as the nitrogen was shut off. The engine was run for 1-2 seconds achieving steady state conditions and then the oxygen flow was shut off first followed by the fuel flow. The engine was then purged with nitrogen which opened as the oxygen closed and was continued for four seconds following the run. This ensured the shutdown was also 'softened' as well. This becomes critical if the engine was shutdown during an abort and the engine will not have additional hardware damage. The modified sequence is shown below.

1. The engine was purged with nitrogen.
2. Ethylene flow was started.
3. Nitrogen purge remained on with the oxygen flow initiated simultaneously with the hydrogen/oxygen torch.
4. Nitrogen was turned off simultaneously with the hydrogen/oxygen torch.
5. The hydrogen/oxygen torch was shut off after 1 second.
6. The engine was run for 1-2 seconds achieving steady state conditions.
7. The oxygen flow was turned off while simultaneously turning on the nitrogen purge.
8. The fuel flow was turned off.
9. The nitrogen purge was turned off after 4 seconds.

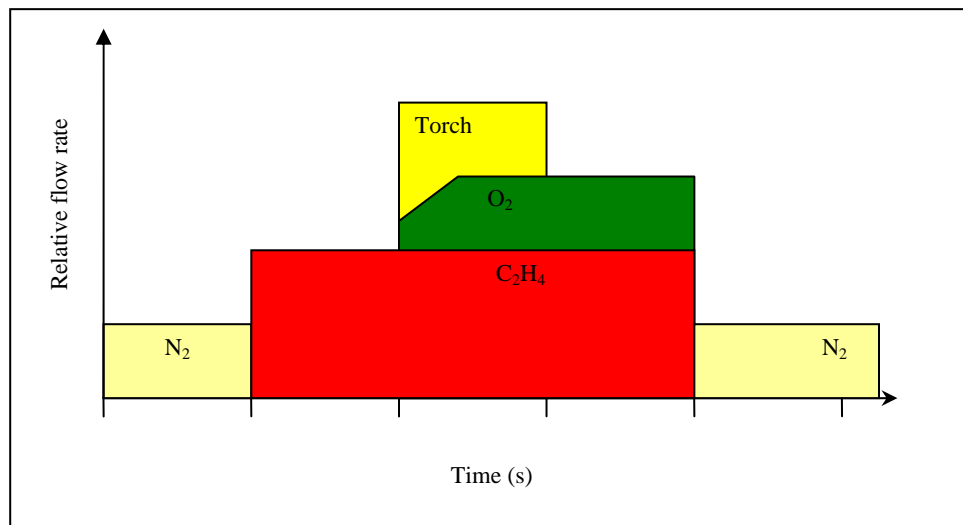


Figure 18. Graphic Representation of the Modified Engine run sequence<sup>1</sup>

The pressure drop across the injector was investigated next to determine whether the beads are affecting the orifice plate. The pressure differential was measured starting from the gaseous input through the bead field and the injector plate. The pressure drop across the injector was designed to be below 15% of the chamber pressure. Sierra Engineering provided a solution of producing a retainer cup for the beads to ensure the 3 mm glass beads would not block the orifice holes.

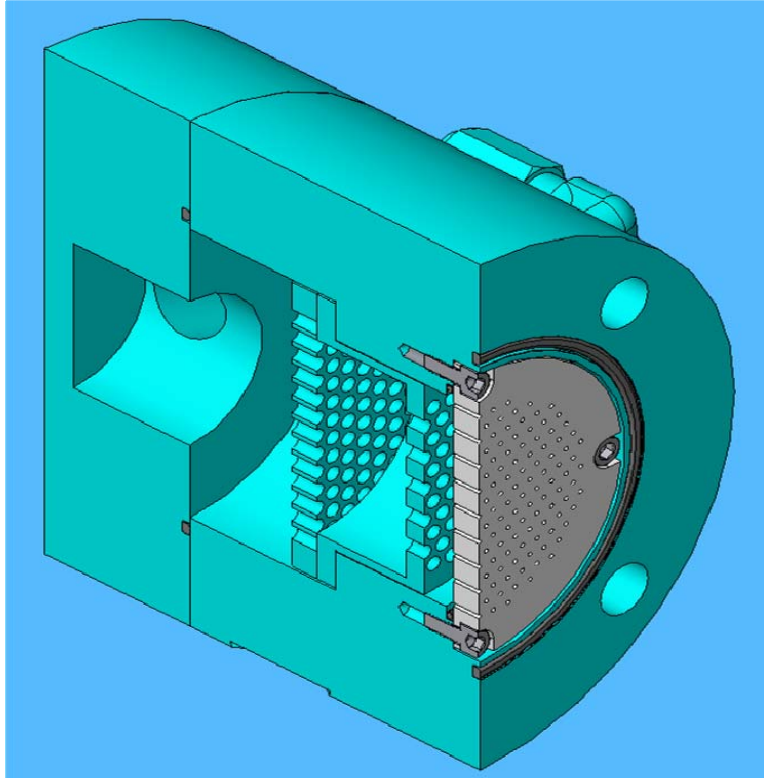


Figure 19. Bead Retainer Cup<sup>1</sup>

Cold flow tests were performed with a mass flow of 0.1589 lb/s and showed a pressure drop of approximately 15.0%. While this was acceptable, it was higher than expected. After the injector was disassembled and inspected, it was noticed the beads neatly rolled into the holes on the retainer cup blocking the holes. This is the same manner as marbles roll across a Chinese checker board. This appeared to be the cause of the higher pressure drop.

Additional cold flow testing was conducted with two stainless steel screens (16 grids per inch) placed together biaxial across the face. This created a flat plane which the beads could lie against and not block the larger holes of the retainer cup. Two more screens were placed on the upstream face in the same manner. The tests were repeated with the same mass flow as the previous tests resulting with only a pressure drop of 7.2 percent. This was a marked improvement of the original design.

The next question posed was whether the orifice plate produced gaseous velocities large enough to keep the flame from flashing back. A cold flow gaseous test was conducted with a hot wire to measure the velocity of the gases off of the injector face. Nitrogen gas was used at a mass flow of 0.12 lb/s. The wire was first placed at 2 mm from the orifice face. The gaseous velocities spiked as it crossed each hole with a maximum in the center of the orifice plate. The velocities were also measured 14 mm from the orifice plate showing the velocities averaged at 220 m/s. An OF ratio of 2.0 has an associated turbulent flame speed of 12.192 m/s, where as the gaseous velocity was 18 times greater which is sufficient for restricting flashback. The results are shown in Figure 20.

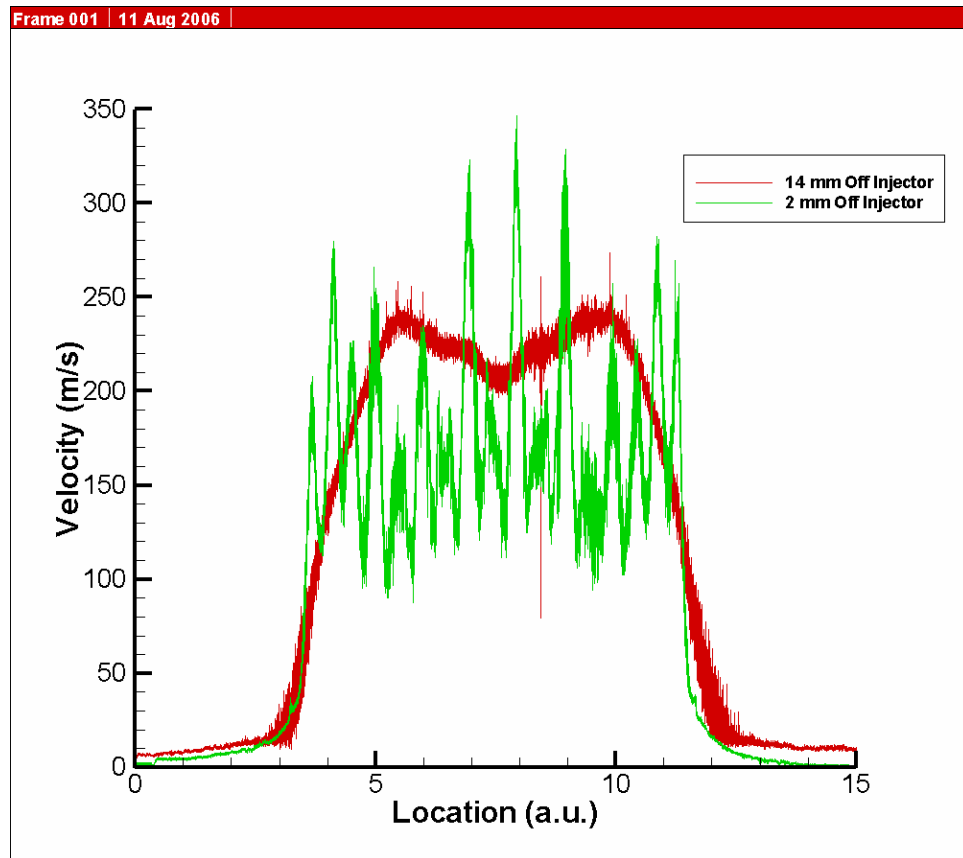


Figure 20. Results of the Hot Wire tests

The last possibility considered was whether the heating of the orifice plate was high enough to autoignite the premixed propellants on the upstream side of the plate. Sierra Engineering performed analysis using a perfectly stirred reactor model and autoignition theory, the minimum auto ignition temperature at stoichiometric conditions was estimated at 1300 R.<sup>1</sup> Under the tested conditions the predicted maximum temperature on the orifice plate is 1050 R. Another case was also analyzed where one-fourth of the orifice holes were blocked; the maximum temperature on the orifice plate was 1200 R. These temperatures are lower than the autoignition temperature of 1300 R and therefore it can be assumed autoignition temperatures on the backside of the orifice plate did not cause combustion in the premixed chamber.

The second injector incorporated all the improvements discussed and was tested at a mass flow rate of 0.2 lb/sec with an OF ratio of 0.8. The second hot fire test of the premixed injector was again unsuccessful. After reviewing the video recording of the run, the connection to the burst disk was glowing immediately following ignition indicating nearly immediate combustion in the premixing chamber. Although the injector was thoroughly tested for cold flow conditions, it was not able to arrest flashback. The source of ignition appeared to originate with the ignition event. Figure 21 shows the connection to the burst disk which was completely consumed during the test.



Figure 21. Burst Disk connection following the second hot fire test

The remains of the injector and orifice plate after the test are shown below in Figure 22.



Figure 22. Injector plate following the second hot fire test

The retainer cup and beads were completely consumed in the run and formed slag in the combustion chamber and is depicted in Figure 23.



Figure 23. Combustion chamber filled with slag of retainer plates and glass beads following the second hot fire test

The Sierra Engineering premixed injector was designed to produce a uniform high velocity bulk flow to be injected into the combustion chamber. The orifice holes were designed at a diameter of 0.026 inches to inject the gaseous propellants at high velocities and quench flashback should it occur. This orifice plate was also made from high temperature stainless steel to withstand the higher temperatures of combustion. This was the correct theory but it was not enough to control flashback, at least during the ignition sequence.

Subsequent literature studies were then performed and a paper written by Orbital Technologies Corporation discovered where they had successfully designed a premixed injector using hydrogen and oxygen. This article published by the AIAA was titled *Premixing Rocket Engine Injectors for High Pressure Gaseous Oxygen and Hydrogen* authored by W. Knuth, D. Gramer and C. St.Clair. In this paper they had two primary approaches to prevent flashback. The first approach was the use of quench distance designs where the injection orifices are smaller than the quench distance of the premixed propellants. The second approach was the aerodynamic designs that inject the mixture velocities above the flame propagation speed.<sup>5</sup> Both of these theories were applied to the design of the current injector, but the aerodynamic design was more dominant in creating the injector.

Quench theory is based on the largest distance between two parallel plates that will extinguish a propagating flame front. The theory is based on these parallel plates being able to transfer heat away from the combustion gases and extinguish the flame. If enough heat is can be taken away from the combustion gases, the temperature of the gases will fall below the ignition temperature of the mixture and the flame will be quenched.<sup>5</sup> While this is a theory that is able to quench the flame, it does not provide much safety margin for flashback especially when large pressure changes are experienced. The quenching distance may still allow the flame to sit on the face of the injector where the flame could tilt and initiate flashback along the slower moving boundary layers. Quenching the flame in this manner is also difficult by the nature of the small dimensions. The quenching distance for Ethylene and oxygen is approximately 0.04724 inch (1.2 mm) which is difficult to machine accurately. Though Orbitec was successful in the quench distance designed injector they were unable to reach chamber



pressures above 65 psi and proceeded with the aerodynamic designed injector. Orbitec was most successful with a porous copper injector. Oxygen free copper has high thermal conductivity and specific heat which efficiently removes the heat from the combustion gases to prevent flashback.<sup>5</sup>

The orifice holes machined on the Sierra Engineering design were appropriate for a quench type injector with a diameter of 0.026 inches, but the injector face was not designed appropriately to remove the heat from the quench zone. The orifice plate was made of high temperature stainless steel, Inconel with a thickness of 0.175 inches. Inconel does not have the high thermal conductivity or thermal inertia required to prevent flashback by the way of the quenching approach.

The aerodynamic designed injector was proven to be the more successful design, where the premixed reactants are injected at velocities greater than the flame speed. This injector design requires close attention to the low velocity boundary layers. This region is where the flame may be able to become tilted and propagate upstream past the injection ports and flashback into the mixing chamber. This is also where active cooling of the injector face was critical for the success of these injectors.<sup>5</sup> It is important to first ensure the gases velocities are kept higher than the flame velocity. Second the injector is able to quench the combustion flame in the advent of flashback. This will be done by keeping the injector holes small, and manufacture the injector from a highly conduction oxygen-free copper and actively cooling the injector.

## **B. CURRENT PREMIXED INJECTOR**

The design of the premixed gaseous engine began with the injector. The successful operation of the premixed injector is the primary goal of this thesis. It is important the propellant gases are thoroughly mixed and then injected at high velocities into the combustion chamber. The first section is the manifold section used to insure the gases are thoroughly mixed where the gases are first introduced in an orthogonal fashion. The oxygen was be injected into the primary flowpath and the ethylene injected at four ports orthogonal to each other and the oxygen flow. The injection of the ethylene should help mix the individual flows as it is injected equally spaced around the core. The mixing will take place as the gases flow the length of ten diameters. The flow will travel four inches in a 0.4 inch diameter section. According to Kuo this will suffice for proper mixing.<sup>3</sup> A smaller port placed upstream is for a burst disk to relieve pressure in the manifold section in case of flashback. If combustion travels upstream beyond the injector into the mixing chamber the propellants could detonate. The burst disk diverts this pressure out of the engine. This part was machined from oxygen-free copper to dissipate heat in the case of flashback.

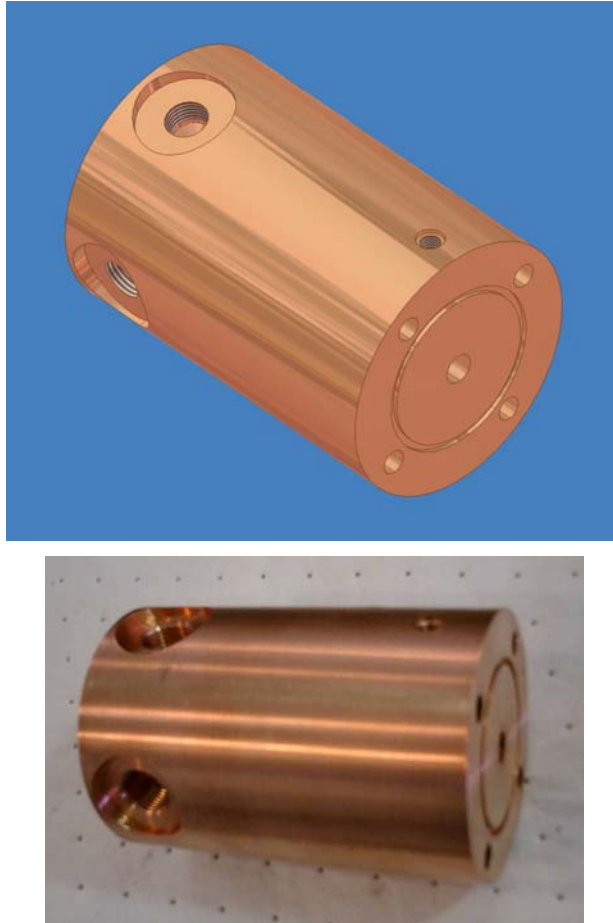


Figure 24. Pictures of the Injector Manifold to thoroughly mix reactants

The next injector section was the Diffuser Chamber which had a diverging cross section with an eight degree half angle to the injector face. The diverging section allows the flow velocity to decrease, decreasing the pressure prior to the injector. Both the Injector Manifold and Diffuser Chamber were manufactured of oxygen-free copper allowing the best conductivity possible in the event that flashback did occur. The inertia conductivity of copper would be able to absorb the heat of combustion until the test was aborted due to flashback. A small port is placed three quarter inches behind the cooled premixed injector face for a thermocouple. The thermocouple was used as a 'Flashback Trigger' which would abort the test if the thermocouple detects a flame. An Omega exposed junction K-type thermocouple was used since they are more sensitive to detect this flame. The abort condition was set 14 degrees above the ambient temperature of the cold gas flow and was our primary means to detect flashback. The Normally Closed

leads from the Omega Programmable Digital Thermocouple Meter (DP25-TC) are wired in series with the Test Cell Three 'Emergency Stop Button.'

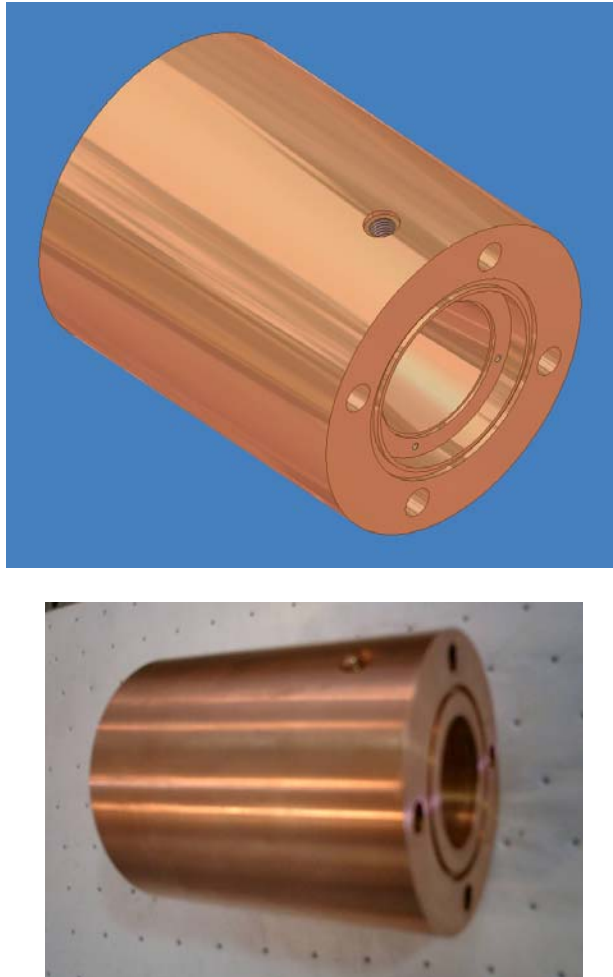


Figure 25. Pictures of the Diffuser Chamber with a 16 degree diverging section

The premixed injector section is a water-cooled injector that is bolted on between the injector manifold and the combustion chamber of the engine. The injector consisted of seven injector tubes that inserted into two injector faces. These faces were sandwiched together with the tubes in between. The tubes have O-ring seals to ensure the water coolant does not come in contact with the propellant effluents. If this were to occur the water could possibly vaporize to steam and cause hardware damage. The sandwiched injector is placed in the Injector housing where it is also sealed by O-ring seals. The seven injector holes are 1/32 inch in diameter and have the ability to be modified to a larger diameter to allow larger mass flows and higher chamber pressures if deemed appropriate. The injector tubes are long in relation to the orifice diameter so in the event of a

flashback the flame has a greater length to travel along the cooler wall. The Injector was also machined from oxygen free copper and the pieces are relatively thick for heat conduction. The water passages around the injector tubes were kept as a large of volume as possible to allow the water to effectively cool the injector tubes and faces. The water output will monitored to detect evidence of flashback as well. Combustion within the injector ports would be indicated by the increase in water temperature. The temperature datum was taken at the beginning of the run prior to ignition. The abort condition was set 8 degrees above the temperature datum. The downstream face will be in contact with the combustion chamber; therefore this is the least sensitive indication. The datum temperature will be the temperature water output prior to ignition. As standard procedure the water cooling will be turned on minutes prior to each shot to ensure the copper has reach thermal equilibrium.

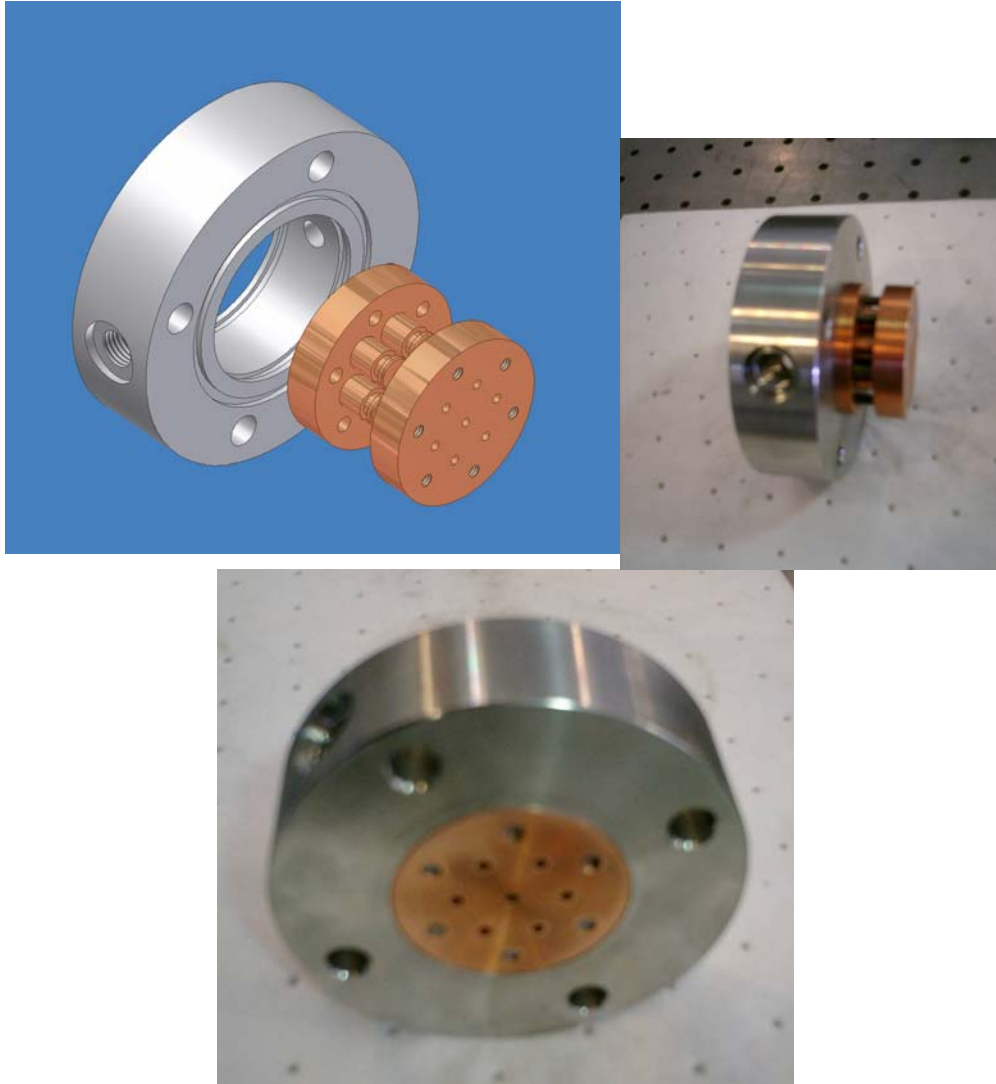


Figure 26. Pictures of the Cooled Premixed Injector

The injector orifices are small diameter smooth-bored holes resulting low Reynolds numbers. This maintains a laminar flow inside the injector with Reynolds numbers less than 2000. The Reynolds is calculated using Equation 2 below.

$$\text{Re} = \frac{lU\rho}{\mu}$$

$l$  = Diameter of tube (m)  
 $U$  = Average velocity of fluid (m/s)  
 $\rho$  = Density of fluid (kg/m<sup>3</sup>)  
 $\mu$  = Viscosity of fluid (m•s /kg)

(2)

Another design parameter of injectors is the discharge coefficient. The discharge coefficient defines the injector's ability to maintain the mass flow through the injector with a minimum of pressure drop across the injector face. High value of discharge coefficients (maximum value of 1.0) are smooth and have well-rounded entrances. These are the most common. The discharge coefficient of our injector is predicted as 0.82. This can be calculated using Equation 3 below.

$$\dot{m} = C_d A \sqrt{\frac{2\Delta p}{\rho}}$$

$\dot{m}$  = Mass flow (kg/s)  
 $C_d$  = Discharge Coefficient  
 $A$  = Area of Orifice (m<sup>2</sup>)  
 $\Delta p$  = Pressure drop across orifice (N/m<sup>2</sup>)  
 $\rho$  = Density of propellant mass flow (kg/m<sup>3</sup>)

(3)

The full assembly of the injector is shown below. The mixing section and the diverging section are rather large and bulky, but can likely be reduced to simple hardware once the premixed injector is better characterized. The three inch combustion chamber and nozzle with 0.3 inch diameter throat was bolted on following the injector. This combustion chamber and nozzle were used and applied as a constant throughout this research.

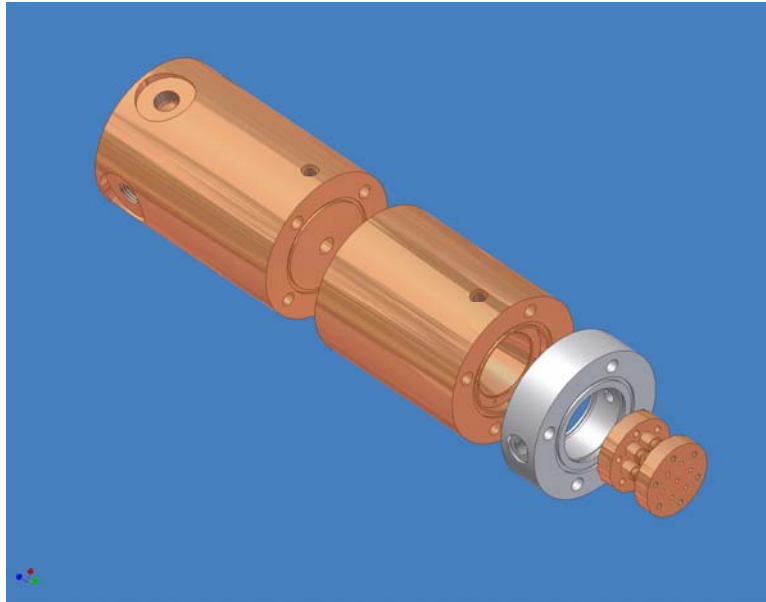


Figure 27. Full Picture of the Cooled Premixed Injector

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## IV. MODELING

### A. SIERRA ENGINEERING PREMIXED INJECTOR

The gaseous flow through Sierra Engineering's premixed injector was modeled using Computational Fluid Dynamics (CFD) software designed by CFDRC and sold by the ESI Group. The geometry of the injector was modeled in three dimensions and meshed using CFD-GEOM where the file can be imported into the appropriate solver. The solver used was ESI Group's CFD-ACE+ to compute the fluid flow and mixing through the mixing chamber. The modeling was completed to understand the gaseous flow through the swirling mixing chamber and to evaluate if the propellants were properly mixed prior to the bead field. This model was created using 500,000 cells.

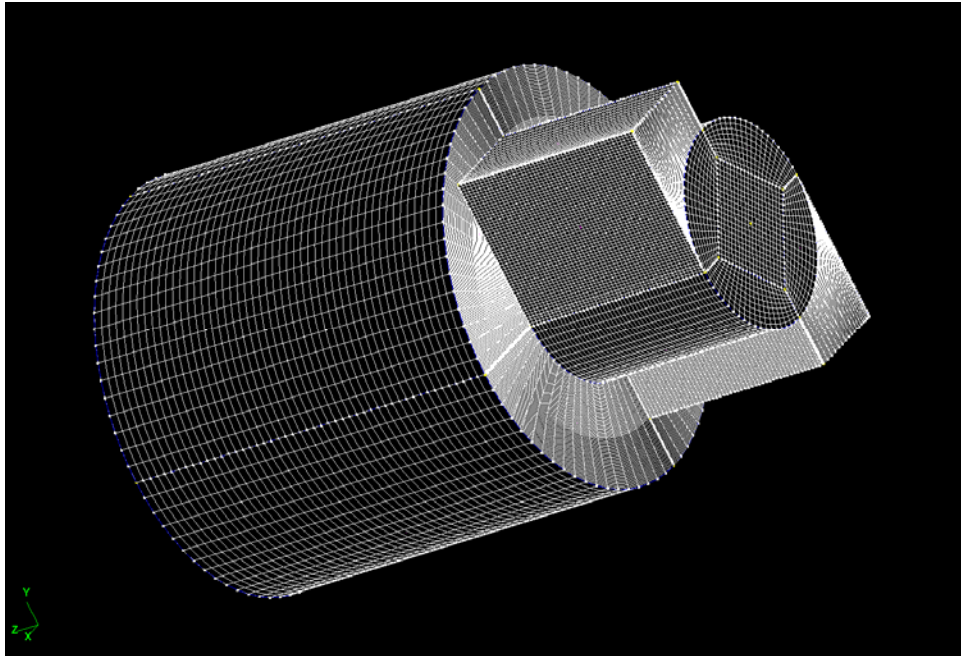


Figure 28. Three dimensional CFD-GEOM model of Sierra Engineering's Premixed Injector

The boundary condition models consisted of a symmetry boundary, wall boundaries, an inlet boundary and an outlet boundary. Once the models were complete they were exported to a \*.DTF file that can be read by a solver program. The initial condition and constraints were then entered into the CFD-ACE+ solver and are listed in Appendix A.

## B. PREMIXED INJECTOR

The premixed injector modeling was completed to understand the gaseous flow through the injectors and to be able to predict the flow field conditions across the engine. The solver used was ESI Group's CFD-FASTRAN to compute the fluid flow through the injector. The injector was drawn in two dimensions as an axis-symmetric geometry to simplify the model assuming rotational symmetry about the longitudinal axis. This also reduces the computational time by assuming this symmetry using 64,000 cells. The CFD-GEOM model produced for this injector is shown in Figure 29.

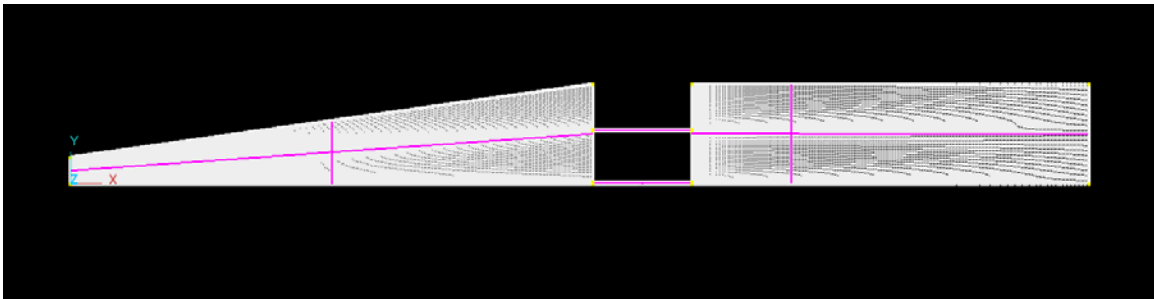


Figure 29. Axis-symmetric CFD-GEOM model of the Premixed Injector

It was important to properly grid the geometry appropriately to ensure the computational resolution is dense around the areas of interest. In this model the density was increased near the injector orifices to ensure proper resolution to properly model the velocity of the downstream gases and more importantly the thin boundary layers at the injector exit. This is to ensure the gaseous velocities are of a sufficiently high magnitude greater than the flame speed. If flashback were to occur it would most likely originate from the slower velocity boundary layers at the exit plane.

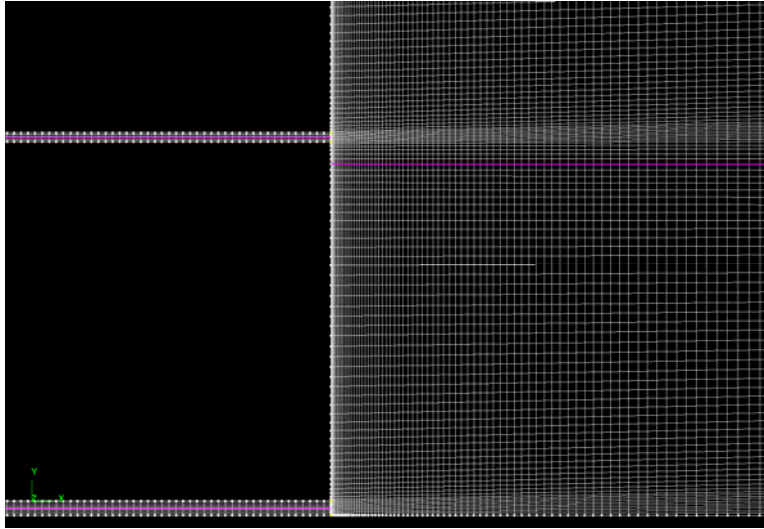


Figure 30. Close up of the orifice exit plane of the Premixed Injector model

These models consisted of a symmetry boundary, wall boundaries, an inlet boundary and an outlet boundary. Once the models were complete they were exported to a \*.DTF file that was read by a solver program. The initial condition and constraints were then entered into the solver which is shown in Appendix A.

### C. CFD NUMERICAL SOLVERS

The setup and simulation for the steady state CFD simulations were performed using CFD-ACE+ and CFD-FASTRAN. These solver codes utilized the Navier-Stokes differential equations discretized over a finite volume. Solving these equations result in a numerical solution of the pressure and velocity through out the specified geometry. CFD-ACE+ is designed for high accuracy in flows with Mach numbers less than 0.8. CFD-FASTRAN is designed particularly for high speed compressible flow but can also do subsonic, sonic and hypersonic flow. The actual set-up for the simulations performed for this research is tabulated in Appendix A, CFD Settings. The settings for each simulation were selected based on initial boundary conditions and given flow parameters of the modeled engine.

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## V. EXPERIMENTAL SETUP

### A. TEST CELL

The testing was conducted in Test Cell (TC 3) at the Rocket Propulsion and Combustion Lab located at the Naval Postgraduate School, shown in Figure 31.



Figure 31. Test Cell Three at the Naval Postgraduate School

This stand is able to support rocket engines up to 250 pounds of thrust and was previously configured for a RP-1/Oxygen engine, although it was easily adapted to support gaseous fuels. The gases are stored along the far wall and are delivered to the table along the floor.

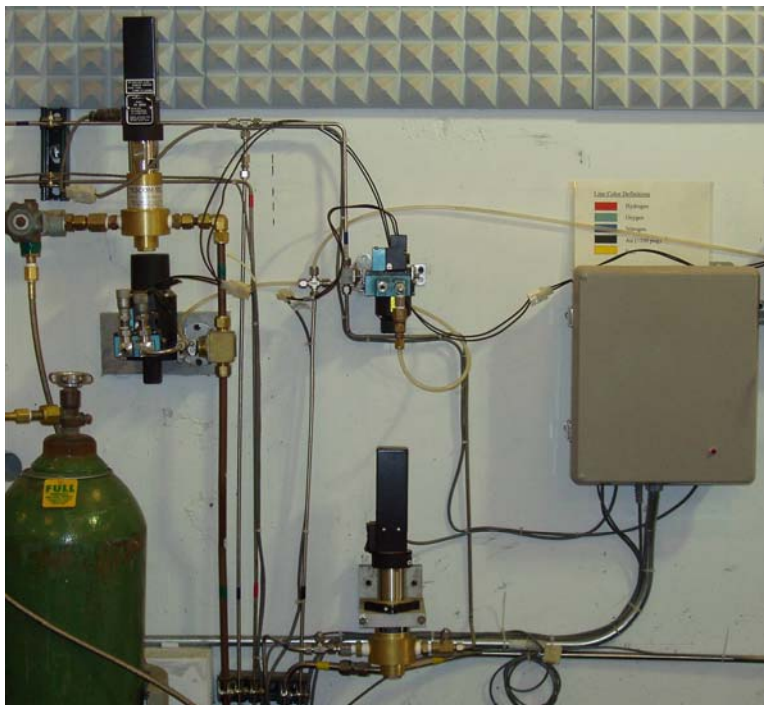


Figure 32. Oxygen and Fuel Regulators and regulator control box

The oxygen and the fuel are regulated prior to being delivered to the table. The remote driven regulators are built by the Tescom Corporation and powered from a 24 volt power supply. Figure 32 shows the regulators and ball valves mounted along the opposite wall which are used to set the pressure of the gases to control the mass flow of the gases for every run. These are controlled using Visual Basic 5.0 program from inside the control room. The controller will be discussed later in more detail.



Figure 33. Accumulator for Ethylene Fuel

Since the ethylene fuel is only provided in bottle pressures of approximately 1200 psi, an accumulator was placed underneath the table to pressurize the fuel for the runs. This accumulator contained a piston and was back-pressurized with nitrogen to ensure if contamination occurs beyond the piston, the gas is inert and there would be no risk of explosion. Nitrogen was supplied in 6000 psi bottles due to the large volume of nitrogen needed to pressurize the accumulator during the runs and decrease the frequency of changing the bottles.

Sonic chokes were used to control the mass flow of the fuel and oxidizer gases. The upstream pressure was set and controlled by the regulators and the flow was monitored by pressure transducers directly upstream and downstream of the choke. This was done to insure the calculated mass flow. The ratio of the upstream to the downstream pressure was held to no less than two to ensure the choke was properly isolated from the downstream conditions. Ethylene was selected as the fuel for being gaseous at room temperature. Though at higher pressures and temperatures ethylene could become supercritical and if so, it can become a two-phase fluid state. Figure 34 shows that ethylene is in a gaseous state above the standard temperature (ST) line and liquid phase below the line. To the right of the critical point the ethylene is supercritical at 731 psi.



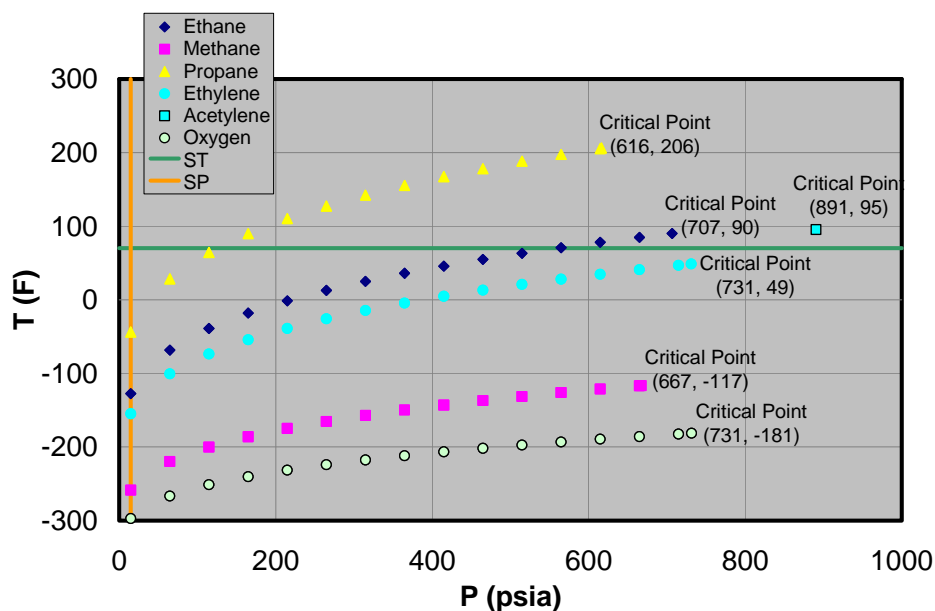


Figure 34. Ethylene Phase diagram<sup>1</sup>

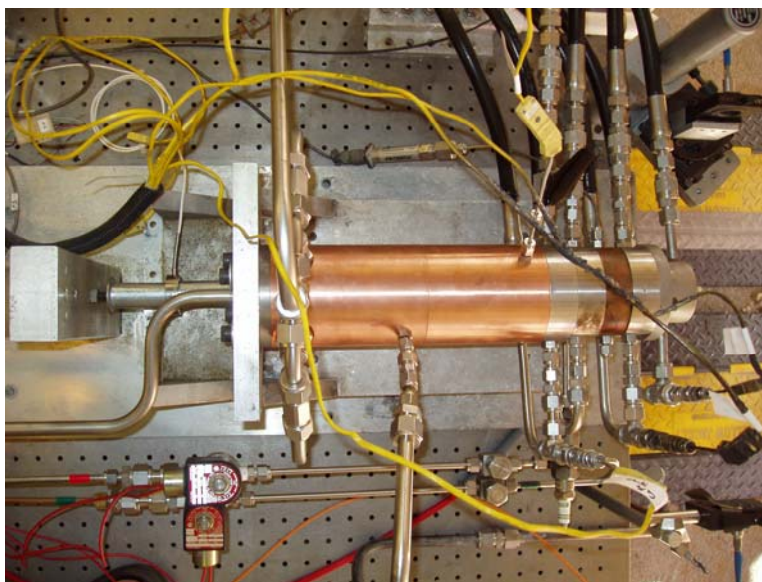


Figure 35. The Non-premixed and Premixed engine in the test stand

Reactants were brought into a non-premixed injector in a coaxial fashion. Since the runs were generally fuel rich, the fuel was injected through the center post with the oxygen coming from the sides at 45 degrees. Oxygen is delivered to the premixed injector through the center core with the ethylene injected through the four off-axis ports.



Top views of both injectors are shown in Figure 35. A thrust transducer rated up to 500 pounds was placed on the forward end of the thrust stand for thrust measurements. The thrust transducer was compressed between the hard points preloading the test stand slightly for more precise reading. The hydrogen/oxygen torch can be seen on the lower portion of the picture and was connected to the injector. The remaining tubing is cooling water for the combustion chamber and nozzle. Thermocouples are used to measure the output temperature of the water cooling. The premixed injector has a couple additional sensors for safety. The ‘flashback trigger’ thermocouple was located three quarters of an inch behind the injector and an additional thermocouple was placed in the water cooling output of the injector. A burst disk rated at 600 psi was also placed in the mixing section.

Figure 36 below shows the style of the non-premixed injector used where there is a center post and two holes impinging at a 45 degree angle inside a 45 degree recess. The hydrogen/oxygen torch entered through the larger hole impinging off the flat face at 45 degrees. The center post had a diameter of 0.118 inches and the two orifice holes had a diameter of 0.0781 diameter. The desired area ratio between the center post and the orifice holes is 1.14.



Figure 36. The Non-premixed injector with center post and two orifices impinging at 45 degrees

The cooling system for the test cell was comprised of a 7.5 HP Baldour motor with a 120 gallon water reservoir piped to the table and is shown in Figure 37.



Figure 37. Water Cooling Pump and reservoir

## B. CONTROLLER

The test cell and the rocket engine were controlled using a PC based program and switches inside the control room. The program used to control the sequence of the rocket engine test runs was generated with Visual Basic 5.0. The program interface also shows a detailed schematic of the engine and the pressures throughout the system which is updated real time.

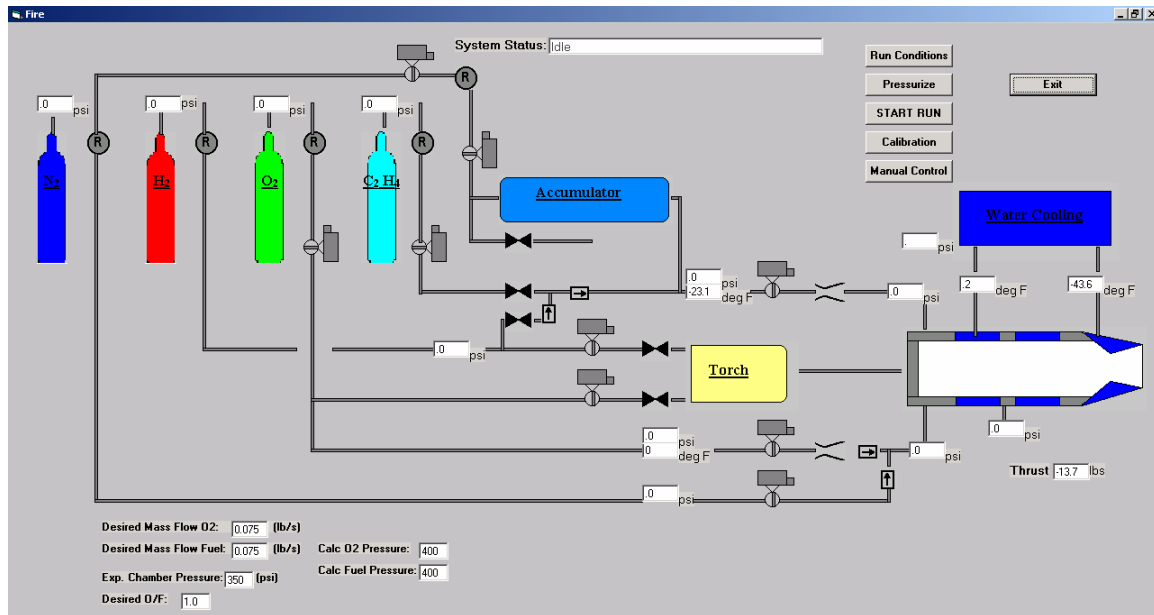


Figure 38. Test Cell Three Controller

The controller was designed where the run inputs were placed in the Run Conditions module and the desired fuel and oxygen pressures are calculated. The inputs to each run are either the desired oxygen and fuel mass flows or the chamber pressure and OF ratio. The run sequence could also be adjusted as shown on the left side of the Run Conditions module. The three second sequence was prescribed as listed previously in the Design Section. The file name is also designated in the caption.

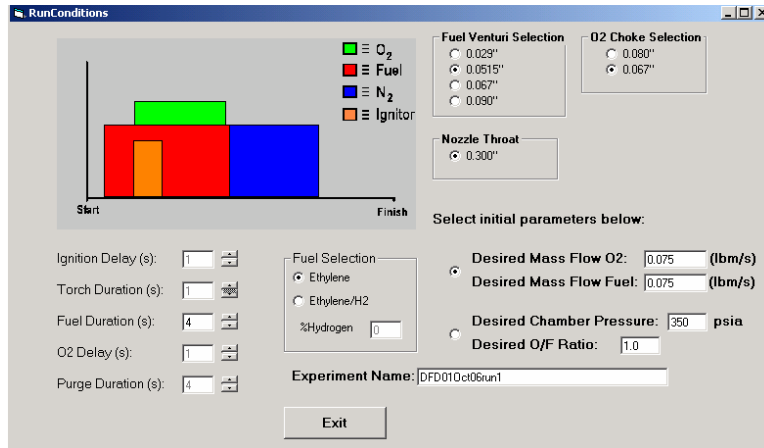


Figure 39. Run Conditions Module

After placing the run inputs and calculating the required pressures, the fuel and oxygen can be pressurized using the Pressurize button. Once the pressures were set, the run sequence was commenced using the Start Run button. Upon pressing the Start Run button the Manual Control Panel was displayed and provided indication of the valves sequencing through the run. The schematic was also updated real-time to show the user the sequence of the run.

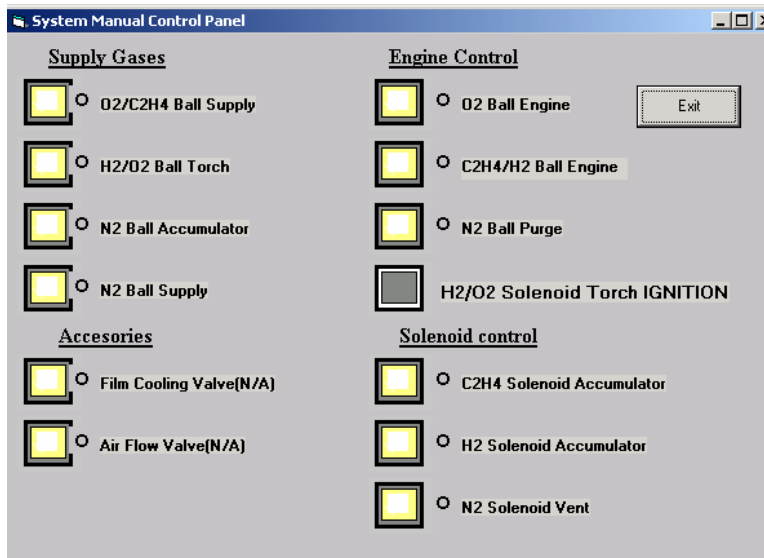


Figure 40. Manual Control Panel Module

The engine controller was based on a National Instruments board NI PCI 6503 placed inside the computer. Master switches for the 24 VDC and 110 VAC power were located in the control room, and the capacity to shutdown the test cell in the event of an emergency was possible through the use of the emergency stop button. The 24 volt DC was used exclusively for the regulator control while the 110 volts AC were used to power the ball and solenoid valves and torch. The 110 volt control lines were passed into the cell and through the control box shown in Figure 41 was mimicked in the control code. The keys on the side of the box control switch between local control inside the test cell or remotely from the control room.



Figure 41. Manual Control Panel

There are two power buses routed through the test cell. These are a 'switched' power bus and an 'unswitched' power bus. The switched power bus is utilized by the controller and is used to actuate the valves to control the gases. The test cell has an emergency stop button or 'kill button', shown in Figure 42, which must be open in order to actuate these valves. When closed, it will close all valves on the table and disables the cell. The kill button is also in series with the 'flashback trigger' which has been previously discussed. The unswitched power was used principally for instrumentation such as pressure transducers, thermocouples and also for cooling water. The cooling

circuits receives it power from the unswitched bus for safety to ensure the engine receives cooling water without the cell being live or kill button out. The pressures and temperatures can also be constantly monitored while the acquisition system is on.



Figure 42. Test Cell Three Emergency Stop button and Cooling Pump switches

### C. DATA ACQUISITION

Data acquisition was accomplished by data acquisition cards located in the computer. A National Instruments PCI MIO-16E-4 board was used to acquire data at 20 Hz over a range of 0-10 VDC and with a 14-bit A/D converter. A National Instrument PCI MIO-16E-1 was used to acquire thermocouple data. The BNC-2090 breakout boxes for both data acquisition cards are shown in Figure 43.



Figure 43. Test Cell Three Acquisition card and Omega Thermocouple meters

The breakout boxes for the NI PCI MIO-16E-1 and NI PCI MIO-16E-4 data acquisition cards are located near the center of the box and can accept up to 16 channels of data. The Programmable Digital Thermocouple meters DP25-TC made by Omega were used to generate a 0-5 VDC analog signal for the temperature and thrust output. The Stanford Research Systems preamplifiers were used to filter the noise from these outputs prior to the acquisition panels.

The flashback trigger was the primary safety device for the premixed injector containing a thermocouple placed behind the injector to detect flashback. This

thermocouple meter was programmed to open the circuit of the kill button if the temperature increased 14 degrees F above a set point indicative of combustion upstream of the injector. Although the primary device to detect flashback was the Exposed K-type thermocouple connected in series with the Test Cell 3 'Emergency stop button', additional techniques were used. The flashback thermocouple was placed three quarter inches behind the injector face and was the most sensitive device to detect whether flashback had occurred and would abort the run within 0.1 seconds. The second detection approach was the water temperature output of the injector face. Since the downstream face was in contact with the combustion chamber the indications were not as accurate as the thermocouple. The last and final detection approach is the burst disk located in the Injector Manifold section. If the pressure rises above the 600 psi rating of the burst disk, this indicates combustion was likely inside the mixing section and the run was aborted.



## VI. RESULTS

### A. CFD RESULTS FOR SIERRA ENGINEERING INJECTOR

The first CFD model generated was the Sierra Engineering premixed injector in a three dimensional model. After the second test, there were a few unanswered questions that were addressed using these simulations. The first issue was whether recirculation zones were formed from the swirling of the propellants. The simulations revealed there was a recirculation zone in the premixed chamber that extended into the entrance of the bead field. The bead field purpose was to further scramble the flow and ensure the flow is uniform across the orifice plate. The negative flow velocity in the core potentially would have an adverse affect on controlling flashback.

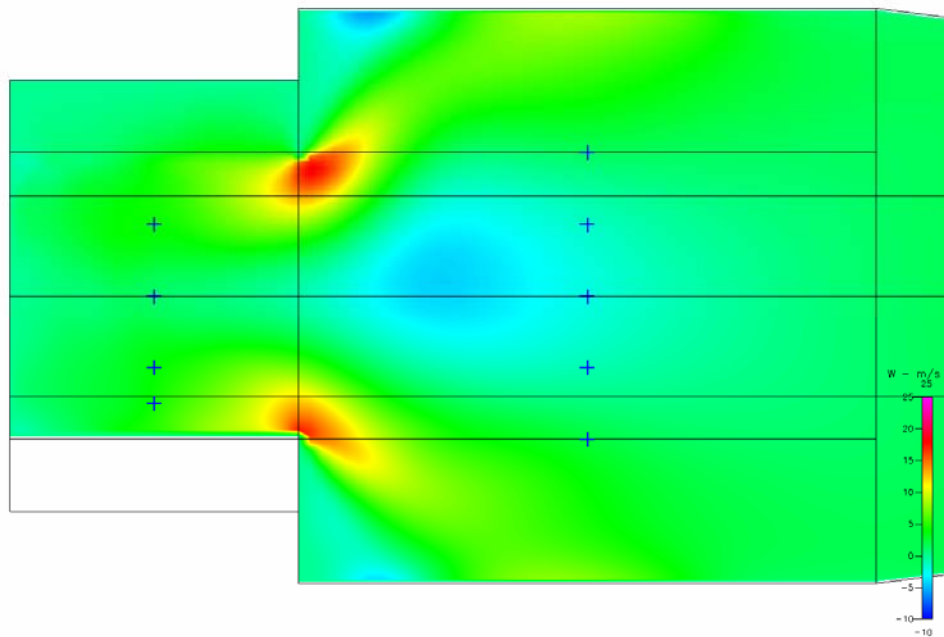


Figure 44. Sierra Engineering Premixed Injector CFD results showing velocity in the Z-plane

An additional issue was whether the propellants were thoroughly mixed by swirling the propellants in the chamber. This was achieved by using the mixing module in CFD-ACE+. The simulation tracked the mixture of the ethylene and oxygen propellants while the velocities and mass fractions were computed. The premixed propellants must meet a uniform OF ratio prior to passing through the injector orifices.

The initial conditions were set for an OF ratio of 1.5. The exit plane should contain a uniform green color signifying these propellants are thoroughly mixed. After analyzing the oxygen mass fraction in the mixture it was quite apparent the propellants were not fully mixed prior to the three-quarter inch bead field. Although the bead field would further mix the propellants, some oxygen-rich regions would likely remain before passing through the injector.

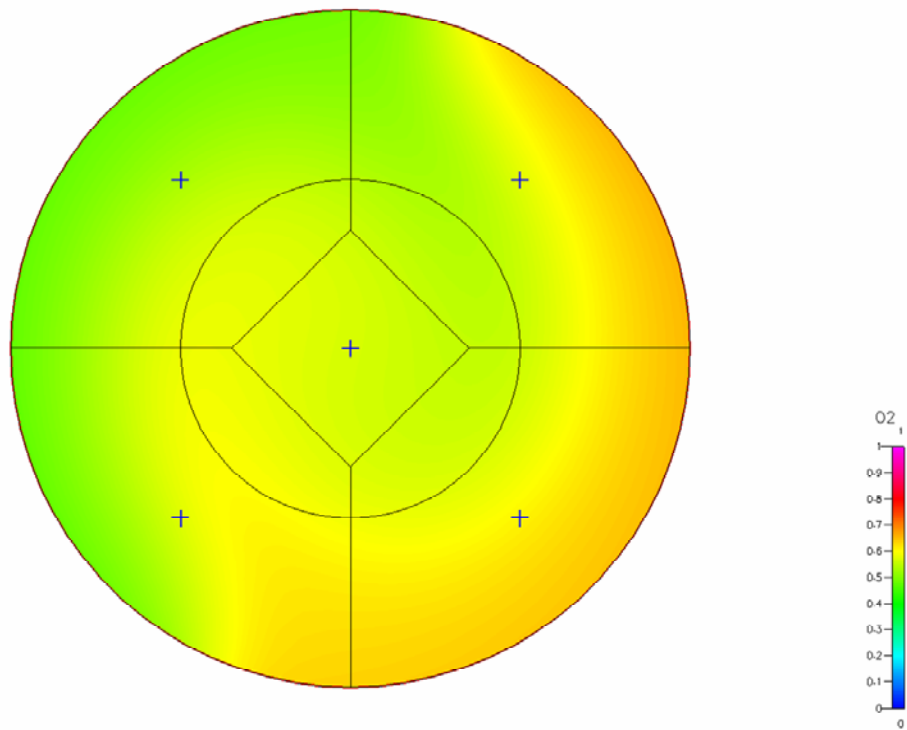


Figure 45. Sierra Engineering Premixed Injector CFD results showing Oxygen concentration at the exit plane prior to bead field

The erosion pattern on the orifice plate from the second run seems to support the non-uniformity analysis, but it is clearly not conclusive. The 1.5 OF ratio had increased non-uniformity producing a greater combustion temperature which consumed the orifice plate. Opposite of the burn-through hole, the residue is dark and sooty signifying a lower OF ratio or fuel-rich combustion. Again, this supports that swirling alone does not adequately premix the propellants prior to the injector. A photo of the orifice plate is shown in Figure 46.

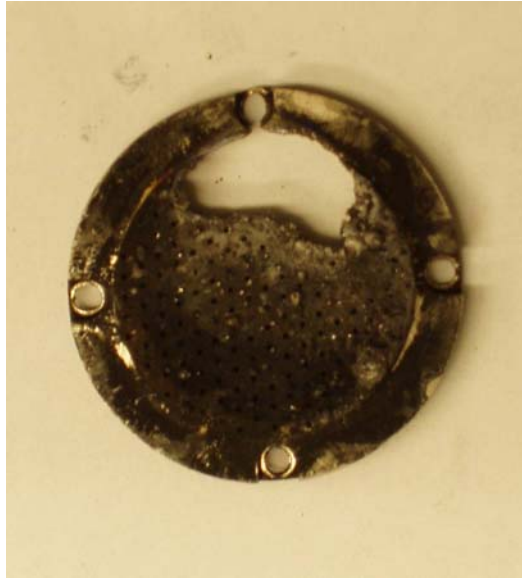


Figure 46. Sierra Engineering premixed injector orifice plate following the second test

## B. CFD RESULTS FOR PREMIXED INJECTOR

The computed premixed injector flow field was solved using CFD-FASTRAN. The results were analyzed for a mass flow of 0.06 kg/s which resulted in an inlet velocity of 40 m/s. This study ensured the velocities of the premixed gases were great enough to resist flashback. The velocity through the orifices peak at 160 m/s and the boundary layers remain thin. There was no presence of large recirculation zones or apparent abnormalities associated with this injector.

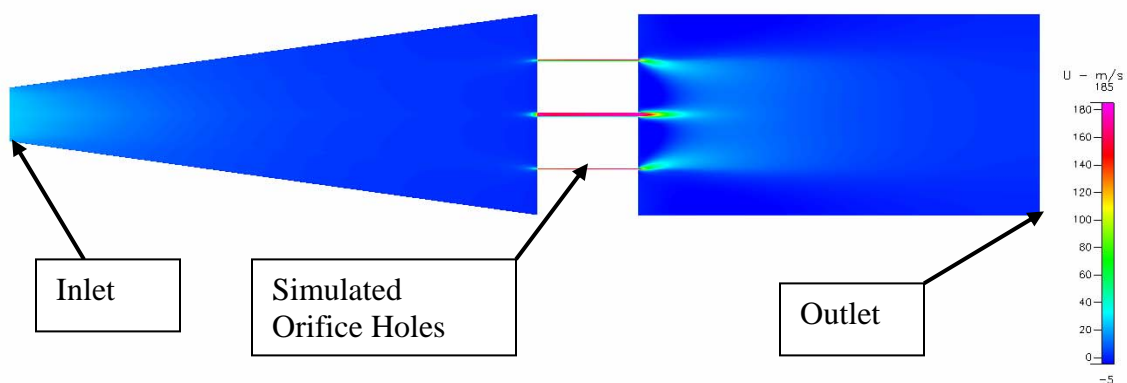


Figure 47. Premixed Injector CFD results showing velocity through the injector

A close up of the orifice provides the details of the flow across the injector face. It was important to focus on the boundary layers of the flow. If there was a pathway for flashback to occur this would be where it would occur. Nominal velocities of 40 m/s along the boundary layer were commonly observed which are greater than the laminar flame speed of 8.0 at an OF ratio of 1.5. This provided a comfortable margin to ensure the flame will not flashback during these conditions.

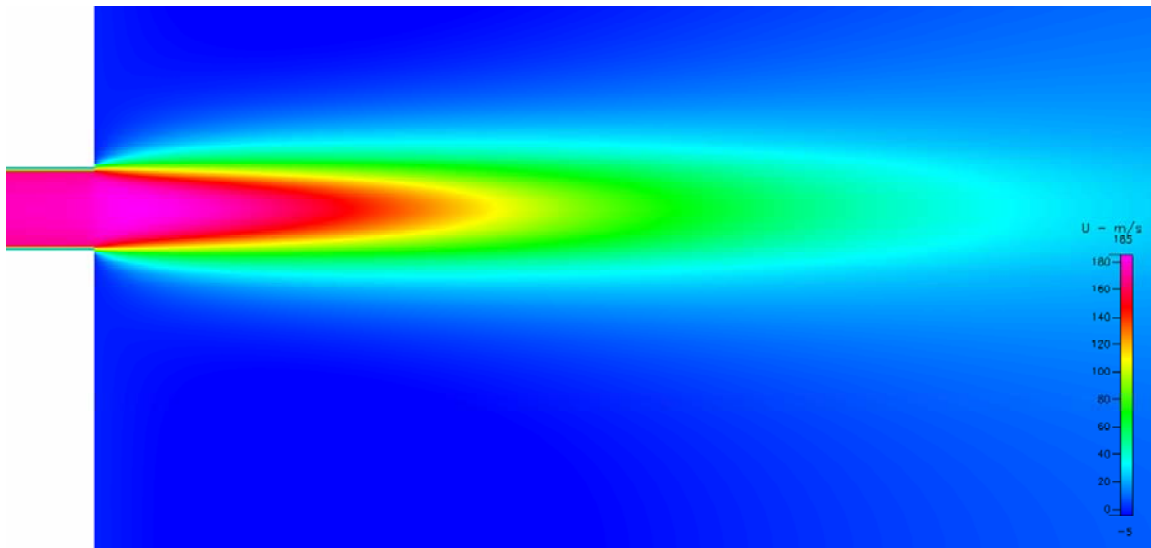


Figure 48. Premixed Injector CFD results showing close up of the velocity profile through the injector orifice

The pressure loss across the injector was also analyzed. A properly designed injector should not have a pressure drop more than 15 %. The resultant pressure drop for the settings used in the CFD model resulted in a pressure drop of 33.5 %. This was a high pressure drop for this injector, but could be relaxed by decreasing the mass flow through the injector or increasing the diameter of the holes. This would allow greater flow rates and greater chamber pressures as well.

### C. LABORATORY

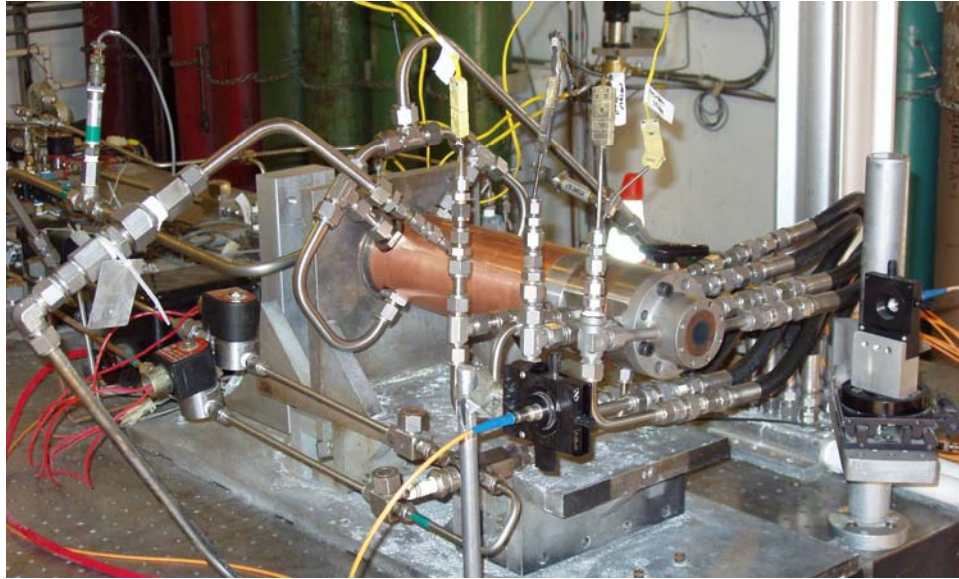


Figure 49. Premixed Injector installed in the test stand

The initial tests with the premixed injector were with the 1/32 inch diameter orifice holes. The diameter selection insures the velocities would remain higher than the turbulent flame velocity. The orifices were also kept at a diameter less than the quenching diameter of 1.2 mm.<sup>2</sup> Seven orifices restrict the total mass flow of the injector. Sonic chokes are utilized to properly meter the mass flow of the propellants upstream of the injector. The maximum mass flow was 0.0236 kg/s through the orifices without unchoking them. The premixed injector was tested successfully with an initial OF ratio of 1.0 with a resulting chamber pressure of 76 psi. These tests were repeated for increasing OF ratio up to 1.8. A sample run is shown below with a total mass flow of 0.0236 kg/s at an OF ratio of 1.2 achieving a chamber pressure of 84.5 psi. The  $c^*$  efficiency was calculated to be 65.8 % for this run. The  $c^*$  efficiency could be increased by lengthening the chamber allowing more time for the propellants to combust due to the high velocities of the fuel jets out of the orifices. Most important though, is that the injector was able to operate correctly with no evidence of flashback.

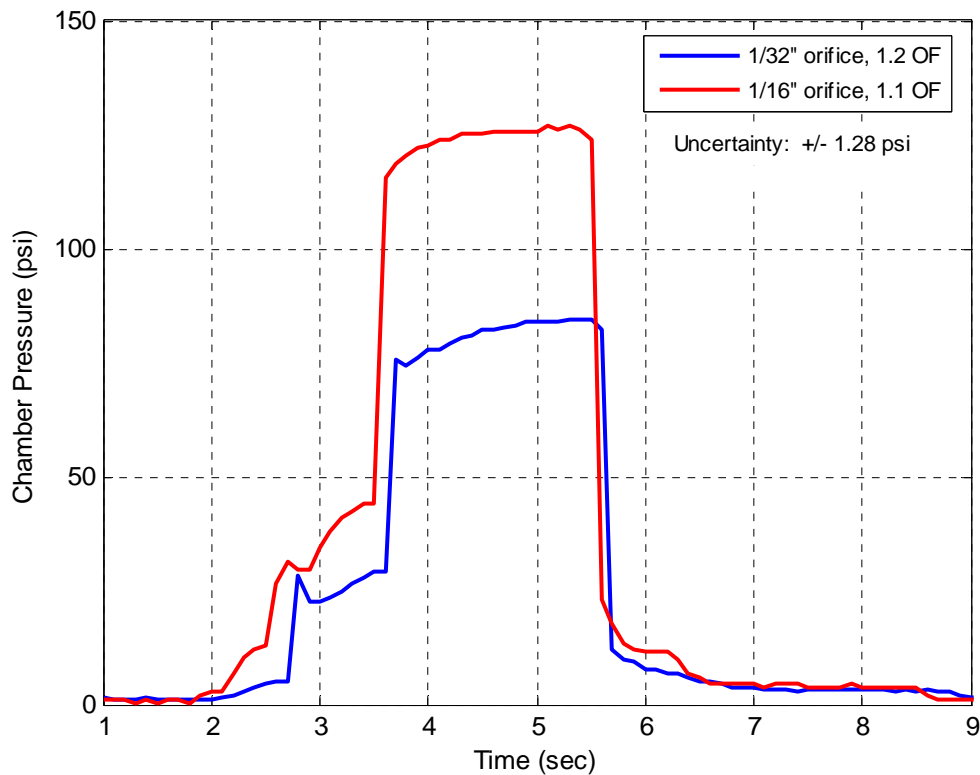


Figure 50. Chamber Pressure Versus Time for Premixed Injector at orifice size of 1/32", mass flow of 0.0236 kg/sec and orifice size of 1/16", mass flow 0.0267 kg/sec

After the preliminary tests, the injector holes were increased to a 1/16 inch diameter. This was to allow a greater mass flow and more reasonable chamber pressures and allow tests more indicative of nominal engine operation. The initial tests were conducted at an OF ratio of 1.0 with a mass flow of 0.0267 kg/sec to allow greater chamber pressures of 126.9 psi. Four successful runs were completed as the OF ratio was increased to 1.1 while holding the mass flow constant. At an OF ratio of 1.2 flashback occurred. The engine was properly shutdown and incurred no damage to the engine or injector. It was evident in these initial tests the gaseous velocities were sufficient to resist flashback.

The tests were continued at a higher mass flow rate. Flashback occurred during the previous runs when the mixing chamber pressure was 182.1 psi achieving a chamber pressure of 125.7 psi. It appears as though the mixing pressure must be at least 56.4 psi greater than the desired chamber pressure achieving a mixture velocity of 89.6 m/s

through the injectors in order to prevent flashback. It also appears imperative that the pressure differential must be greater than 56.4 psi across the injector plate to run the engine without flashback. These guidelines are a function of the OF ratio since the flame velocity increases with OF, and appears to be independent of orifice size. Attempting to increase the chamber pressure is not a limitation of the premixed injector but of the test stand. The area of the orifice chokes cannot be greater than half of the area of the injector to ensure proper metering of the reactants. The total area of the chokes used for ethylene and oxygen must be half of the total area of the injector of  $1.3855 \times 10^{-5} \text{ m}^2$ . The maximum allowable upstream pressure of the ethylene fuel was 800 psi due to the fuel becoming supercritical and preventing accurate flow metering using sonic chokes. The maximum upstream pressure of the oxygen was limited to 820 psi due to the allowable range of the regulator. Currently the maximum chamber pressure that can be achieved in this test cell at this condition is 300 psi.

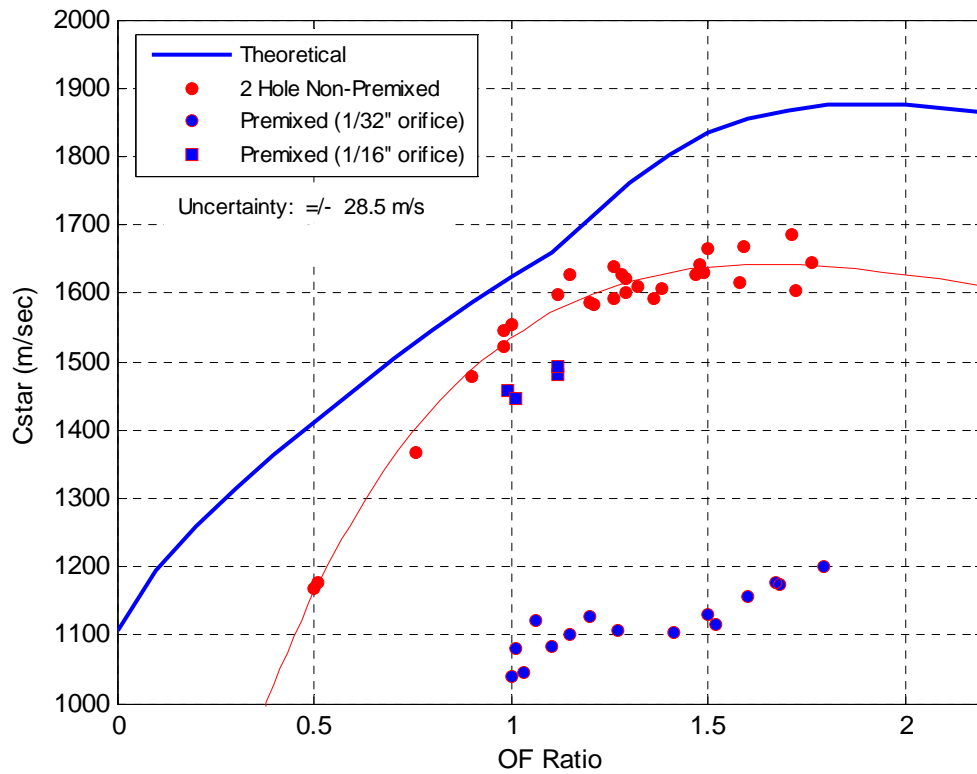
#### **D. C\* EFFICIENCY ANALYSIS**

In determining the performance of the engine, the  $c^*$  data was calculated and monitored. The  $c^*$ , or the characteristic velocity is a means of quantifying the energy released of the propellants. The theoretical  $c^*$  for a given propellant is primarily a function of propellant composition and combustion chamber design independent of the nozzle. Although by knowing the chamber pressure achieved for a given mass of reactants as well as the nozzle throat area, the experimental  $c^*$  can be calculated using Equation 4 as well as the  $c^*$  efficiency. These tests utilize the same combustion chamber and nozzle. The  $c^*$  data in this report only reflects the injector's ability to inject, mix and combust propellants into the engine to achieve as complete combustion as possible.

$$c^* = \frac{p_c A_t}{\dot{m}}$$

$c^*$  = Characteristic velocity (m/s)  
 $p_c$  = Chamber pressure (N/m<sup>2</sup>)  
 $A_t$  = Area of nozzle throat(m<sup>2</sup>)  
 $\dot{m}$  = Mass flow (kg/s)

$$\eta_c^* = \frac{c_{EXP}^*}{c_{THEORY}^*}$$



The equation to approx the  $C^* = f(OF)$  for the 2-Hole Injector is :  
 $1319.651 - 1103.079 e^{(-OF)} + 1688.362 (OF)^* e^{(-OF)}$

Figure 51. Calculated  $c^*$  Versus OF Ratio for the Injectors tested

The preliminary testing and analysis of the premixed engine produced encouraging results. The premixed injector with the 1/32 inch orifices has consistent data points which correlate with the theoretical data obtained from Cequel. The results for the premixed injector with the 1/16 inch orifices appear to improve results due to the slower



velocities emerging from the orifice plate. It was expected to achieve a maximum  $c^*$  efficiency of 98 %, but so far this has not been achieved with the limited testing. A  $c^*$  efficiency of 90.1 % was achieved with a chamber pressure of 126.9 psi, and would increase further by increasing the chamber pressure and the chamber length which would allow the propellants to combust completely.

## E. CARBON SOOT ANALYSIS

The soot analysis was completed using a tunable diode laser diagnostic built by Power Technologies, Inc aimed across the plume centerline. This laser was designed to view in the visible spectrum in 404, 431, 535, 635, and 781 nanometer wavelengths. Utilizing Mie Scattering theory, the diagnostic quantifies the Sauter Mean Diameter of the soot and soot concentration of the products. In a conventional rocket engine using hydrocarbon RP-1 as a fuel, the spectral radiance of the plume is quite high as shown in the Figure 52. The presence of a blackbody component is clearly seen in this figure.

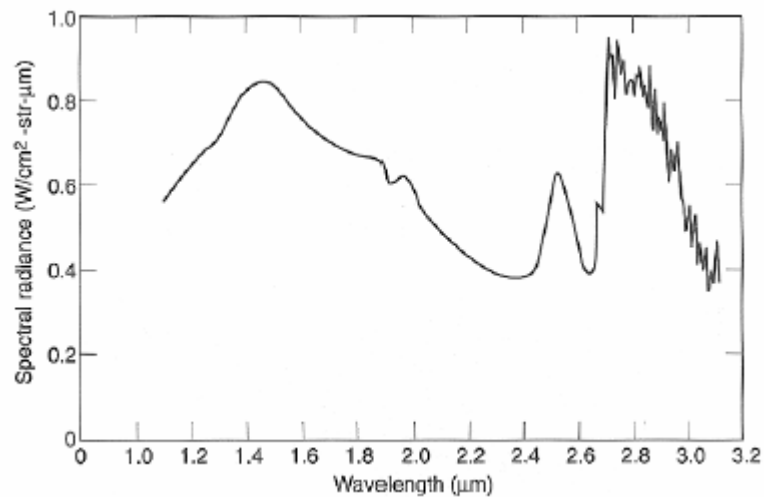


Figure 52. Spectra of RP-1/O<sub>2</sub> rocket plume from an Atlas Booster<sup>8</sup>

The soot concentrations from typical hydrocarbon fuels range from 3 % to 20 % depending on the engine configuration. This soot can be easily distinguished by the visible orange emission rocket plume. This plume can be governed by the reaction shown below. The Spectra radiance is indicative of a 'blackbody', with magnitudes

depending on the particle sizes and concentrations. These liquid hydrocarbon fuels are not very homogenous and are mixed using 'like-on-like' injectors. The mixing that takes place involves the atomization of the liquid RP-1 into clouds that expand into one another, while being heated and evaporated by hot gases.<sup>8</sup> The mixing in the combustion chamber produced richer and leaner regions than what is desired overall.

If the same rocket engine was also tested with ethyl alcohol which is known to produce very little soot, the emission profile is quite different and is evident in Figure 53.

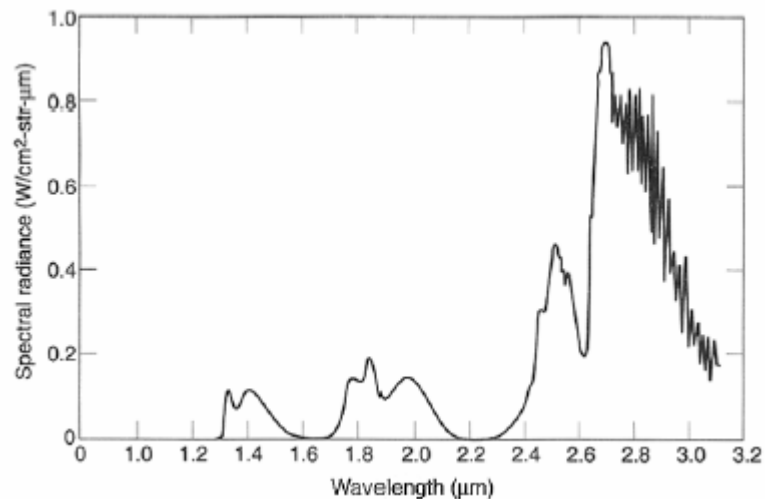


Figure 53. Spectra of  $C_2H_5OH/O_2$  rocket plume from an Atlas Booster<sup>8</sup>

The spectral radiance has maximums which occur at various wavelengths due to molecular emission, but the integrated Spectral radiance is much lower than the broadband emission observed using RP-1. The difference of spectra radiance between the ethyl alcohol and the RP-1 directly correlates to the increased soot production of RP-1, which is due to better mixing of the reactants and the ability to burn to completion producing minimal amounts of soot.

The diagnostic analysis performed determines how well the propellants are combusting within the engine. Ideally the propellants should completely combust with little soot; levels no higher than what equilibrium combustion predicts. The diagnostic was operated and the data reduced by Albert Stowe in his efforts towards his thesis. The average soot sizing was defined by the Sauter mean diameter,  $D_{32}$ . The soot concentration was analyzed as well. The figures only show the results of the non-

premixed engine. Unfortunately the laser failed after the testing of the non-premixed injector. It would be expected the data for the premixed injector would have smaller soot particles and lower soot concentrations than the curves shown. Since the products receiving full mixing prior to the combustion process, the soot production would be limited to chemistry and not atomization and fuel-rich gradients which are the intention of this project. The theoretical data provided was obtained using Cequel which assumes the propellants undergo complete combustion. The underlying goal for this premixed injector was to premix the gases prior to the combustion chamber in an effort of gaining full chemical potential of the propellants by achieving complete combustion.

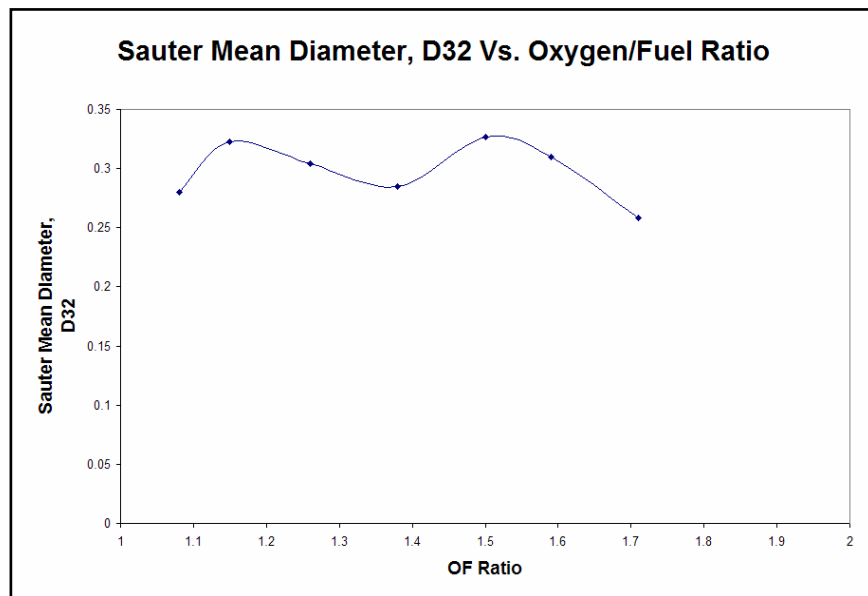


Figure 54. Sauter Mean Diameter Versus OF Ratio for Non-Premixed Injector

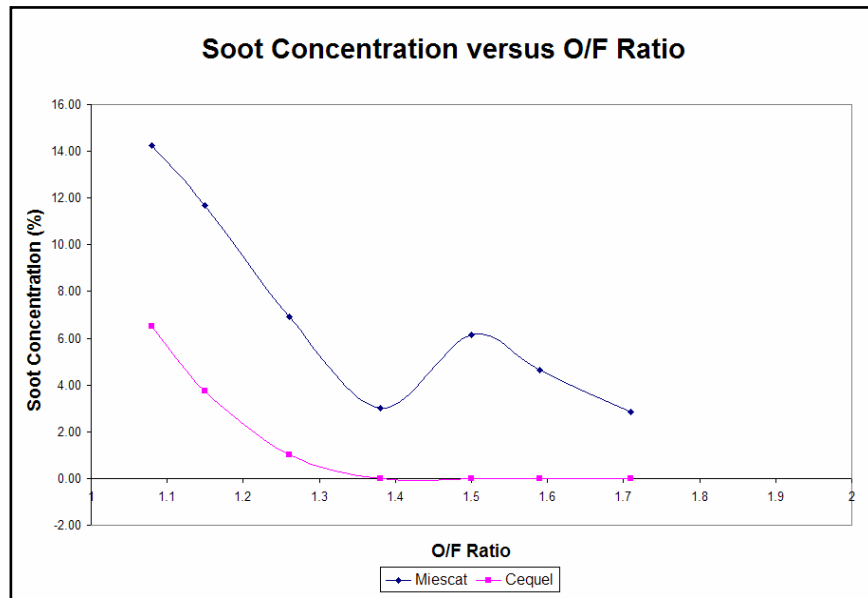


Figure 55. Soot Concentration Versus OF Ratio for Non-Premixed Injector

## VII. CONCLUSIONS

The initial testing of a premixed injector operated on ethylene and oxygen was unsuccessful; the causes of the engine failure were studied and determined. The premixed injector was discovered to likely have had partial blockage of the flow condition screen, non-uniform mixing, and recirculation zones which are believed to have caused non-homogenous conditions to occur across the injector face. These observations provided guidance and were considered during the design of a water-cooled premixed injector for ethylene and oxygen which proved to be successful during the initial testing. Theories of quenching and flame stability were carefully applied throughout the design process. Quenching theory was used as a means to maintain small orifices to resist flashback and to insure heat was removed from the injector, while flame stability was studied to insure the velocities of the mixture was maintained greater than the expected flame velocities. The designed premixed injector with 1/32 inch diameter orifices operated at mass flow rates of 0.024 kg/sec achieving chamber pressures of 76 psi at OF ratios ranging from 1.0 to 1.8 without propensity of flashback. The injector was further tested with 1/16 inch diameter orifices at an increased flow rate of 0.027 kg/sec and was able to achieve chamber pressures of 127 psi and  $c^*$  efficiencies of 90.1 %. At an OF ratio of 1.2 flashback was observed where the average mixture velocity was less than 89.6 m/s. The preliminary investigation of the cooled premixed injector demonstrated this design fueled by a homogenous mixture of ethylene and oxygen can be successfully operated and used to better understand and accurately model the chemical mechanisms that produce soot, but careful consideration must be given if the injector is to be used for higher chamber pressures or mixtures with higher flame speeds.

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## VIII. FUTURE WORK

The designed premixed engine did not reach the desired operating pressure or OF ratio for the ethylene/oxygen mixtures. Future tests should determine the orifice diameter limits of the premixed injector with nominal chamber pressures along the OF ratio range of 1.0 to 1.8. Accurate soot measurements should be made to provide soot production curve information for the premixed chamber. Studies should also evaluate the required combustion chamber length to achieve the maximum experimental  $c^*$ .

Local heat transfer studies near the injector plate could analyze the amount of heat needed to be removed from the premixed injector in order to operate within the given limits and generate a better understand the role quenching has in the successful operation of the injector.

Other mixing techniques could be utilized to reduce the mass and dimensions of the hardware required to operate this premixed injector. This may be achieved upon characterizing the full operation limits of the injector to incorporate a more 'compact' engine design.

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## APPENDIX A: CFD SETTINGS

CFD-ACE+ Settings				
SierraMixingChamberPlusT_1.5.dtf				
<b>Problem Settings</b>				
Modules:		Flow		
		Turbulence		
		Chemistry/Mixing		
<b>Model Options</b>				
Shared:		Steady state		
Flow:		Reference Pressure:		100,000 Pa
Turb:		Turbulence Model		K Epsilon, Schmidt Num 0.9
		Chemistry Model		Gas Phase, Species Mass Fraction
<b>Volume Conditions</b>				
Physical Properties:	Property Mode			Fluid, Gas
	Density Evaluation Method			Ideal Gas Law
	Viscosity Evaluation Method			Constant, 1.846E-5 kg/m-s
	Chemistry (Mass diffusivity)			Schmidt Num 0.7
<b>Boundary Conditions</b>				
Inlet (1):	Mode			Constant
	Pressure			120000
	Temperature			300 K
	Relative Pressure			Constant, 100,000 Pa
	y-direction velocity			-6 m/s
	Kinetic Energy			0 m <sup>2</sup> /s <sup>2</sup> (Default)
	Dissipation Rate			0 m <sup>2</sup> /s <sup>3</sup> (Default)
	Chemistry			EthyleneGas
Inlet (2):	Mode			Constant
	Pressure			180000
	Temperature			300 K
	Relative Pressure			Constant, 100,000 Pa
	y-direction velocity			6 m/s
	Kinetic Energy			0 m <sup>2</sup> /s <sup>2</sup> (Default)
	Dissipation Rate			0 m <sup>2</sup> /s <sup>3</sup> (Default)
	Chemistry			OxygenGas
Wall:	x, y, z -direction velocity			0 m/s (Default)
Symmetry:				0 m <sup>2</sup> /s <sup>2</sup> (Default)
Interface:				0 m <sup>2</sup> /s <sup>3</sup> (Default)
Outlet:	Flow			Fixed Pressure
	Pressure			140000
	Temperature			300 K
	Kinetic Energy			0
	Dissipation Rate			0
	Chemistry			Air
<b>Initial Conditions</b>				
Initial Condition:	User specified			AMG
IC Applied:	For all volumes			CGS+Pre (Default)
Shared:	Temperature			300
Flow:	z-direction velocity			2 m/s
	Pressure			140000
Turb:	Turbulence Intensity			0.05
	Dissipation Rate			100000 m <sup>2</sup> /s <sup>3</sup>
Chem:	Mixture Specification			Air
<b>Solver Control</b>				
Iterations:	Max Iterations			1000
	Convergence Criteria			0.0001 (Default)
	Min Residual			1E-18 (Default)
Spatial Differencing:	Velocity			Upwind (Default)
Solvers:	Velocity			CGS+Pre (Default)
	P Correction			AMG
	Turbulence			CGS+Pre (Default)
Relax:	Velocities			0.2
	P Correction			0.2
	Pressure			1
	Density			1
	Viscosity			1
Limits:				Maintain default settings
Advanced:				Maintain default settings
Output:	Steady state results			specified interval (50 iterations)
Print:	Mass flux summary			YES
Graphic:				Default + Species Mass fractions
Monitor:				Default settings

Table 2. CFD-ACE+ Solver settings for Sierra Engineering Injector

CFD-FASTRAN Settings			
BasicPremixed.Full.Final_40.dtf			
Problem Settings			
Problem Type:		Compressible Flow	
Model Options			
Global:		Axisymmetric	
Flow:		Gas Model	Ideal Gas
		Viscous Model	Turbulent (Navier Stokes)
Ideal Gas Properties:		Molecular Weight	28.97 g/mol
		Gamma, (C <sub>p</sub> /C <sub>v</sub> )	1.4
		Viscosity, Mu	Constant (Dynamic), 1.71e-5
		Conductivity, Pr	0.7
		Turulent Conductivity, Pr <sub>t</sub>	0.9
		Turbulence Model	K Epsilon (Wall Func)
Volume Conditions			
Physical Properties:		Property	Fluid
Boundary Conditions			
Wall:		Heat Transfer	Adiabatic
		Flow Condition	No slip
Symmetry:		Maintain default settings	
Interface:		Maintain default settings	
Inlet:		Mode	Fixed Total Pand T
		U	40 m/s
		V	0 m/s
		Static Pressure	2640000 N/m^2
		Static Temperature	300 K
		Kinetic Energy	0 m <sup>2</sup> /s <sup>2</sup> (Default)
		Dissipation Rate	0 J/kg.s
Outlet:		Flow, Fixed Pressure	1800000 N/m^2
Initial Conditions			
Flow:		Initial Condition from:	Constant
Volume by Volume		U	10 m/s
Zones 2		V	0 m/s (Default)
Entrance Vol		Static Pressure	2640000 N/m^2
		Static Temperature	300 K
Initial Conditions			
Flow:		Initial Condition from:	Constant
Volume by Volume		U	200 m/s
Zones1,3		V	0 m/s (Default)
Injector Tubes Vol		Static Pressure	1000000 N/m^2
		Static Temperature	300 K
Initial Conditions			
Flow:		Initial Condition from:	Constant
Volume by Volume		U	5 m/s
Zones 4		V	0 m/s (Default)
Exit Vol		Static Pressure	2400000 N/m^2
		Static Temperature	300 K
Solver Control			
Control:		Steady-State	
Simulation:		Max Number of Cycles	10000
		Zonal Subcycles	1 (Default)
		Convergence Crit.	1.0 e-20
Time Step:		Based on CFL Number	
		Initial CFL	0.1
		Final CFL	1
		Ramping Cycles	100 (Default)
Spatial: Flow		Flux Splitting	Roe's FDS
		Spatial Accuracy	First Order
Entropy Fix		Linear Waves	0.2
		Nonlinear Waves	0.2
Solvers: Flow		Time Integration	Implicit
		Implicit Scheme	Point Jacobi (Fully Implicit)
		Subiterations	20
		Tolerance	0.0001
		Discretization	Backward Euler
Linear Relaxation:		No settings	
Advanced:		Freeze flow field	Unchecked
Output			
Output: Solution Data		Specified Interval	100 cycles/steps
		Unique files	
RSL, Force, etc		Overwrite	
Print:		Aero Force Summary	Unchecked
		Aero Force by Section	Unchecked
Monitor:		Monitor Points	Unchecked
Graphic:		No settings	

Table 3. CFD-FASTRAN Solver settings for Premixed Injector

## APPENDIX B: WIRING TABLES

### **PCI-MIO-16E-4 (Device 1)**

500 (Ks/sec)

ACH0	Nitrogen Pressure on Table (N2Pressure)
ACH1	Fuel Manifold Pressure (C2H4ManifoldPressure)
ACH2	Chamber Pressure (ChamberPressure)
ACH3	Ethylene Pressure on Table (C2H4Pressure)
ACH4	Ethylene Supply Pressure (C2H4SupplyPressure)
ACH5	Hydrogen Supply Pressure (H2SupplyPressure)
ACH6	O2 Manifold Pressure (O2ManifoldPressure)
ACH7	Nitrogen Supply Pressure (N2SupplyPressure)
ACH8	Oxygen Pressure on Table (O2Pressure)
ACH9	Thrust (Thrust)
ACH10	Water Cooling Pressure (WaterPressure)
ACH11	Not in use (FuelFilmSet)
ACH12	Oxygen Supply Pressure (O2SupplyPressure)
DAC1OUT	Output to Computer

### **PCI-MIO-16E-1 (Device 2)**

1.25 (Ms/sec)

ACH0	Water Temperature at Injector (InjectorTemp)
ACH1	Not in Use (FuelFilmMani)
ACH2	Water Temperature at Chamber (WaterTempChamber)
ACH3	Water Temperature at Nozzle (WaterTempNozzle)

### **Omega Thermocouple Meter**

2	N.C.1 to Test Cell #3 Kill button (Normally Closed 1)
3	Comm1 from Test Cell #3 Kill button (Common 1)

## 68-Pin MIO I/O Connector Pinout

This figure shows the pinout of 68-pin B Series and E Series devices. The following B Series and E Series devices use this pinout:

- NI 6013
- NI 6014
- NI 6015 Mass Termination
- NI 6023E
- NI 6024E
- NI 6030E
- NI 6032E
- NI 6034E
- NI 6035E
- NI 6036E
- NI 6040E
- NI 6052E
- NI 6062E
- NI 6070E
- PCI-MIO-16E-1
- PCI-MIO-16E-4
- PCI-MIO-16XE-10
- PCI-MIO-16XE-50

If you are using the R6850 or SH6850 cable assemblies with 68-pin E Series devices, refer to the [50-Pin MIO](#) pinout.



**Note** Further documentation for the B Series devices is located in the *E Series Help*.



**Note** Some hardware accessories may not yet reflect the revised terminal names. If you are using an E Series device in Traditional NI-DAQ (Legacy), refer to the [Terminal Name Equivalents](#) table for information on Traditional NI-DAQ (Legacy) signal names.

AI 8	34	68	AI 0
AI 1	33	67	AI GND
AI GND	32	66	AI 9
AI 10	31	65	AI 2
AI 3	30	64	AI GND
AI GND	29	63	AI 11
AI 4	28	62	AI SENSE
AI GND	27	61	AI 12
AI 13	26	60	AI 5
AI 6	25	59	AI GND
AI GND	24	58	AI 14
AI 15	23	57	AI 7
AO 0 <sup>1</sup>	22	56	AI GND
AO 1 <sup>1</sup>	21	55	AO GND
AO EXT REF <sup>1</sup>	20	54	AO GND
P0.4	19	53	D GND
D GND	18	52	P0.0
P0.1	17	51	P0.5
P0.6	16	50	D GND
D GND	15	49	P0.2
+5 V	14	48	P0.7
D GND	13	47	P0.3
D GND	12	46	AI HOLD COMP
PFI 0/AI START TRIG	11	45	EXT STROBE
PFI 1/AI REF TRIG	10	44	D GND
D GND	9	43	PFI 2/AI CONV CLK
+5 V	8	42	PFI 3/CTR 1 SRC
D GND	7	41	PFI 4/CTR 1 GATE
PFI 5/AO SAMP CLK	6	40	CTR 1 OUT
PFI 6/AO START TRIG	5	39	D GND
D GND	4	38	PFI 7/AI SAMP CLK
PFI 9/CTR 0 GATE	3	37	PFI 8/CTR 0 SRC
CTR 0 OUT	2	36	D GND
FREQ OUT	1	35	D GND

<sup>1</sup> No connects appear on pins 20 through 22 of devices that do not support AO or use an external reference.

Figure 56. PCI-MIO-16E-1 Data Acquisition Pin Assignments

### NI 6503

Some hardware accessories may not yet reflect the NI-DAQmx terminal names shown here. If you are using a device in Traditional NI-DAQ (Legacy), refer to the [Terminal Name Equivalents table](#) for the Traditional NI-DAQ (Legacy) signal names.

P2.7	1	2	GND
P2.6	3	4	GND
P2.5	5	6	GND
P2.4	7	8	GND
P2.3	9	10	GND
P2.2	11	12	GND
P2.1	13	14	GND
P2.0	15	16	GND
P1.7	17	18	GND
P1.6	19	20	GND
P1.5	21	22	GND
P1.4	23	24	GND
P1.3	25	26	GND
P1.2	27	28	GND
P1.1	29	30	GND
P1.0	31	32	GND
P0.7	33	34	GND
P0.6	35	36	GND
P0.5	37	38	GND
P0.4	39	40	GND
P0.3	41	42	GND
P0.2	43	44	GND
P0.1	45	46	GND
P0.0	47	48	GND
+5 V	49	50	GND

Figure 57. NI 6503 Data Acquisition Pin Assignments

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## APPENDIX C: TEST CELL #3 SOP

### Standard Operating Procedure Test Cell #3

#### Facility Open Procedure

1. RED “Emergency Stop” Button – IN
2. “RPL03” computer, Stanford Amplifiers, Black Box Power strip(Inside) – ON
3. “Dave Cell 3 Control” – EXECUTE
4. Enter “Calibrate” Forms and Ensure Fuel and O2 Regulators – 0 Psi
5. 24 VDC Power Supply (Control Room)- ON
6. Yellow Flashing Alley Lights – ON
7. Ensure Ethylene, Oxygen, Hydrogen, Nitrogen bottles are Full
8. Black Box Power strip(Test Cell #3) – ON
9. Ensure Toggle switches – ALL UP
10. Regulator Supply Power (Under Box, Red Light ON) – ON
11. ORIEL electronics, Video, Thermal Imaging cameras (verify connections) – ON

#### In Test Cell #3

12. Ensure Cooling Water Supply valves are directed for Test Cell #3
13. Shop Air (Rear wall, green handle) – ON
14. Ethylene, Oxygen, Hydrogen, Nitrogen bottles - OPEN
15. Set Hydrogen, Ethylene Pressure Regulator - Approx 700 psi
16. Ensure Igniter and Ignition Solenoids are connected
17. Cue Video, Thermal Imaging cameras and other Diagnostic Equipment
18. EVACUATE ALL PERSONNEL FROM TEST CELLS
19. RED “Emergency Stop” Button – RESET
20. Enter “Run Conditions”
  - a. Ensure Fuel Venturi, O2 Choke, and Nozzle Throat are correct
  - b. Ensure Run Sequence is correct
  - c. Set Fuel Selection
  - d. Set Initial Parameters:
    - i. Mass Flow O2 and Mass Flow Fuel (lbm/sec)
    - ii. Chamber pressure (psi) and O/F Ratio
  - e. CHANGE EXPERIMENT NAME “DFD\_date\_Run# “
21. Enter “Calibration”
  - a. Ensure O2 and Fuel Pressures are correct
  - b. “Mix Fuel” – PRESS
22. “Pressurize” - PRESS
23. Ensure Golf Course is Clear
  - a. VCRs - RECORD
  - b. Cooling Pump – ON
  - c. Siren – ON

**\*\*\*\*\*WARNING\*\*\*\*\***

**Next step commences rocket ignition**

24. “START RUN” - PRESS

After Run

25. RED “Emergency Stop” Button – IN  
26. Ensure all Valves are closed on “Manual Control” Form  
27. Siren – OFF  
28. VCR’s – STOP  
29. Ensure all Valves are closed on “Manual Control” Form  
30. Ensure FlashBack Trigger was not set (#1)  
31. “Facility Operation” – EXIT

Securing Facility

32. RED “Emergency Stop” Button – RESET  
33. Enter “Calibrate” Form and Ensure Fuel and O2 Regulators – 0 Psi  
34. RED “Emergency Stop” Button – IN  
35. Cooling Pump – OFF  
36. “Dave Cell 3 Control” – EXIT  
37. Ethylene, Oxygen, Hydrogen, Nitrogen bottles - CLOSE  
38. Shop Air (Rear wall, green handle) – OFF  
39. Video, Thermal Imaging cameras and other Diagnostic Equipment - OFF  
40. Yellow Flashing Alley Lights – OFF  
41. Test Cell #3 Door - CLOSE



APPENDIX D: ENGINEERING DRAWINGS

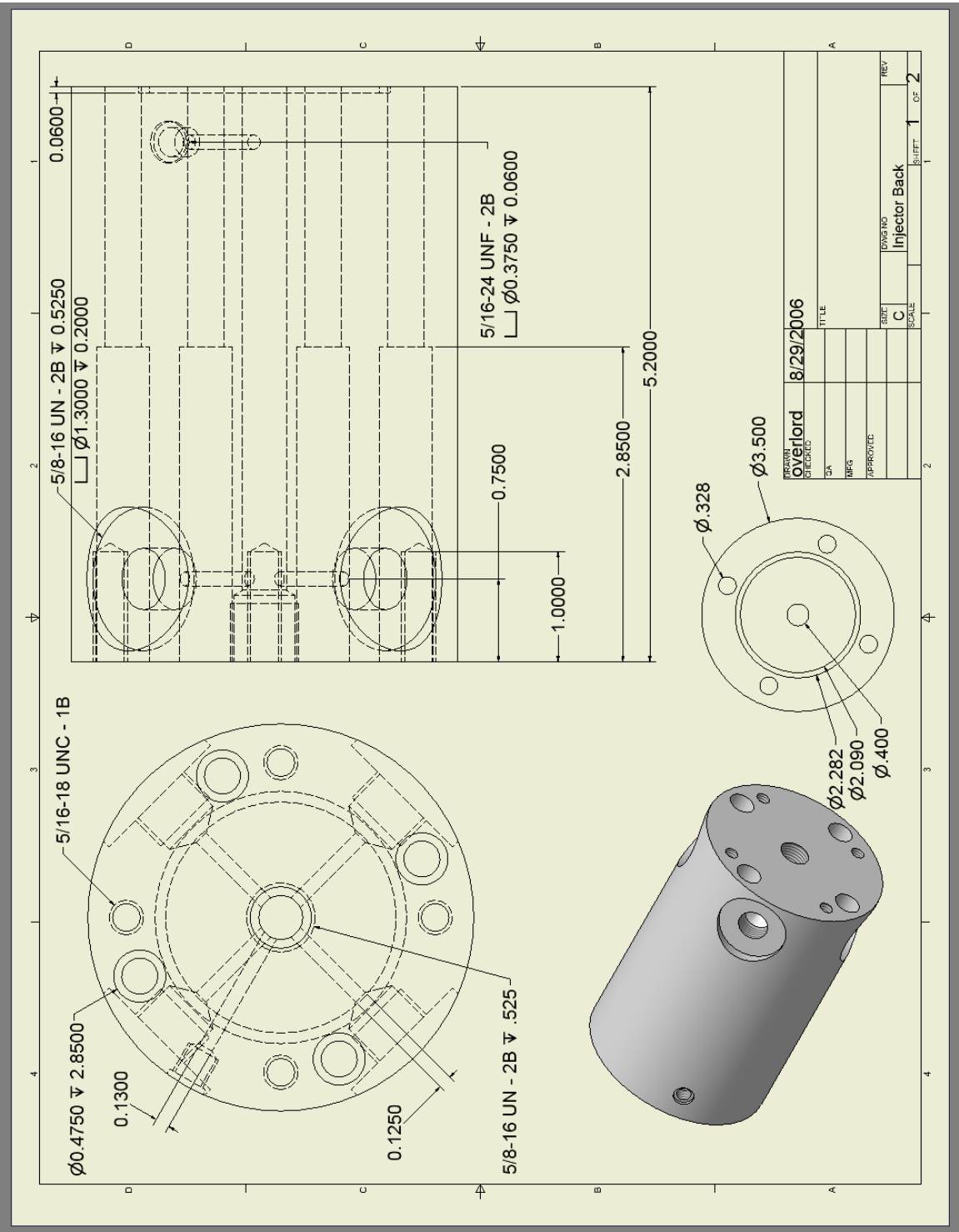


Figure 58. Premixed Injector Manifold Section



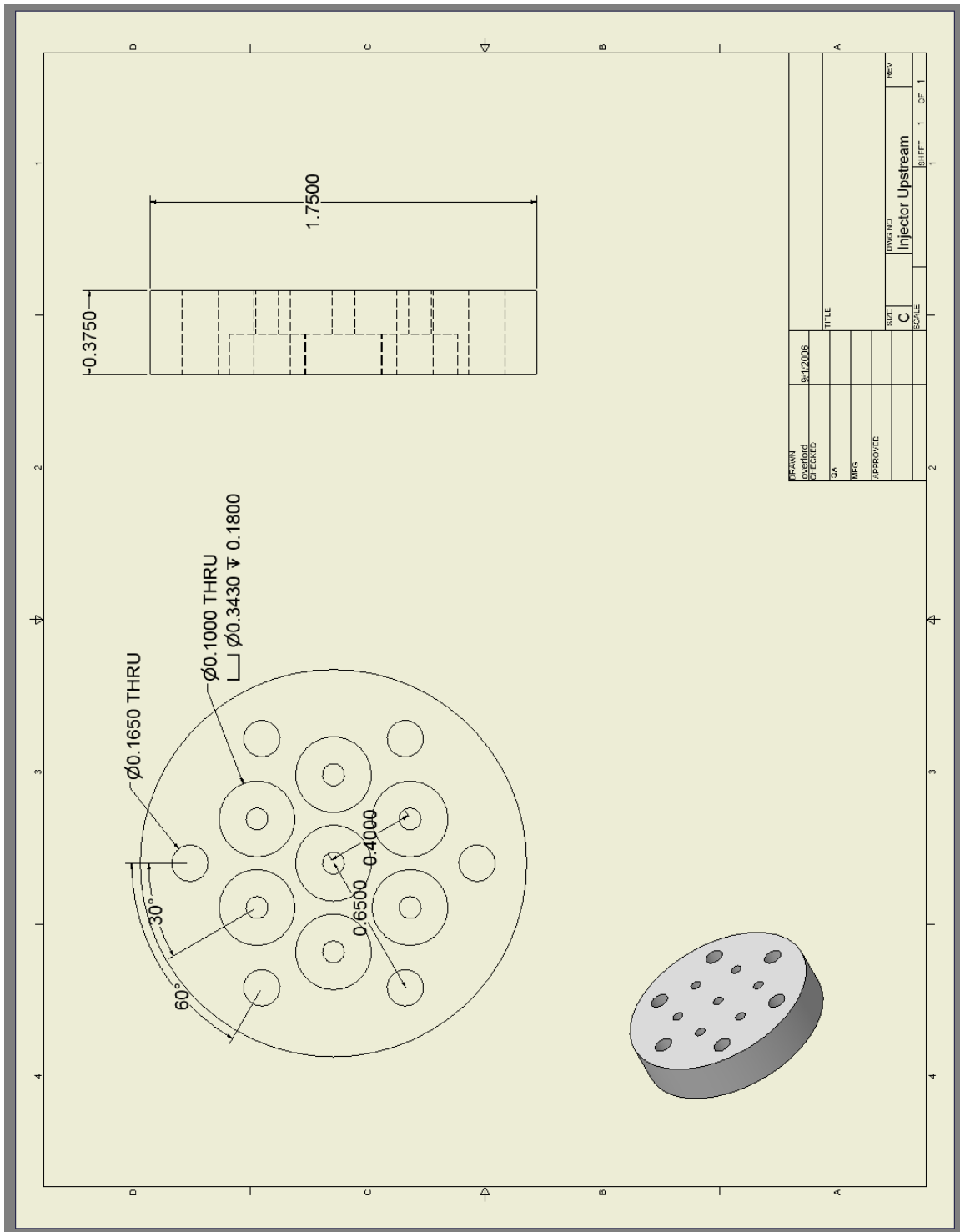


Figure 60. Injector Plate Upstream



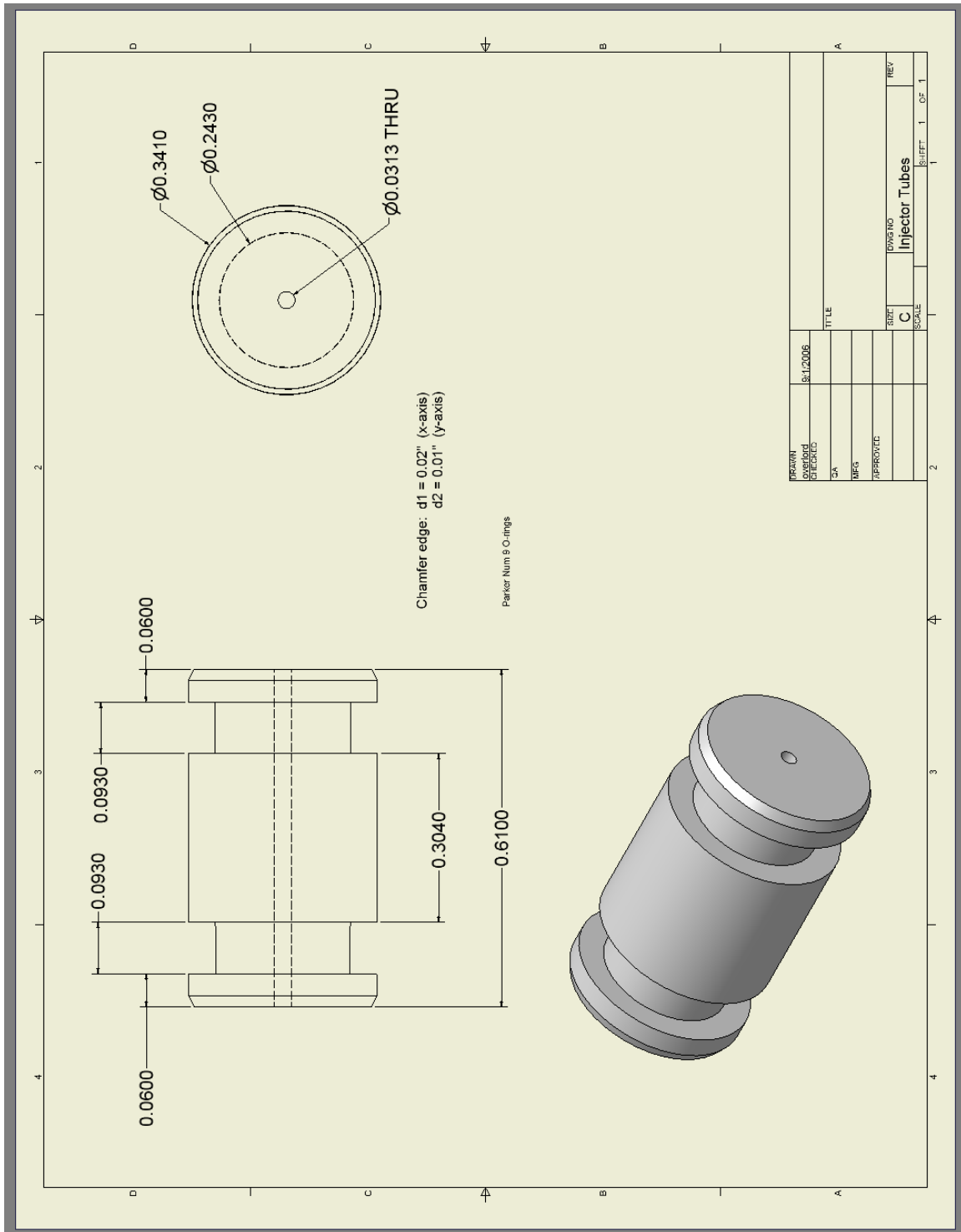


Figure 62. Injector Orifice Tubes



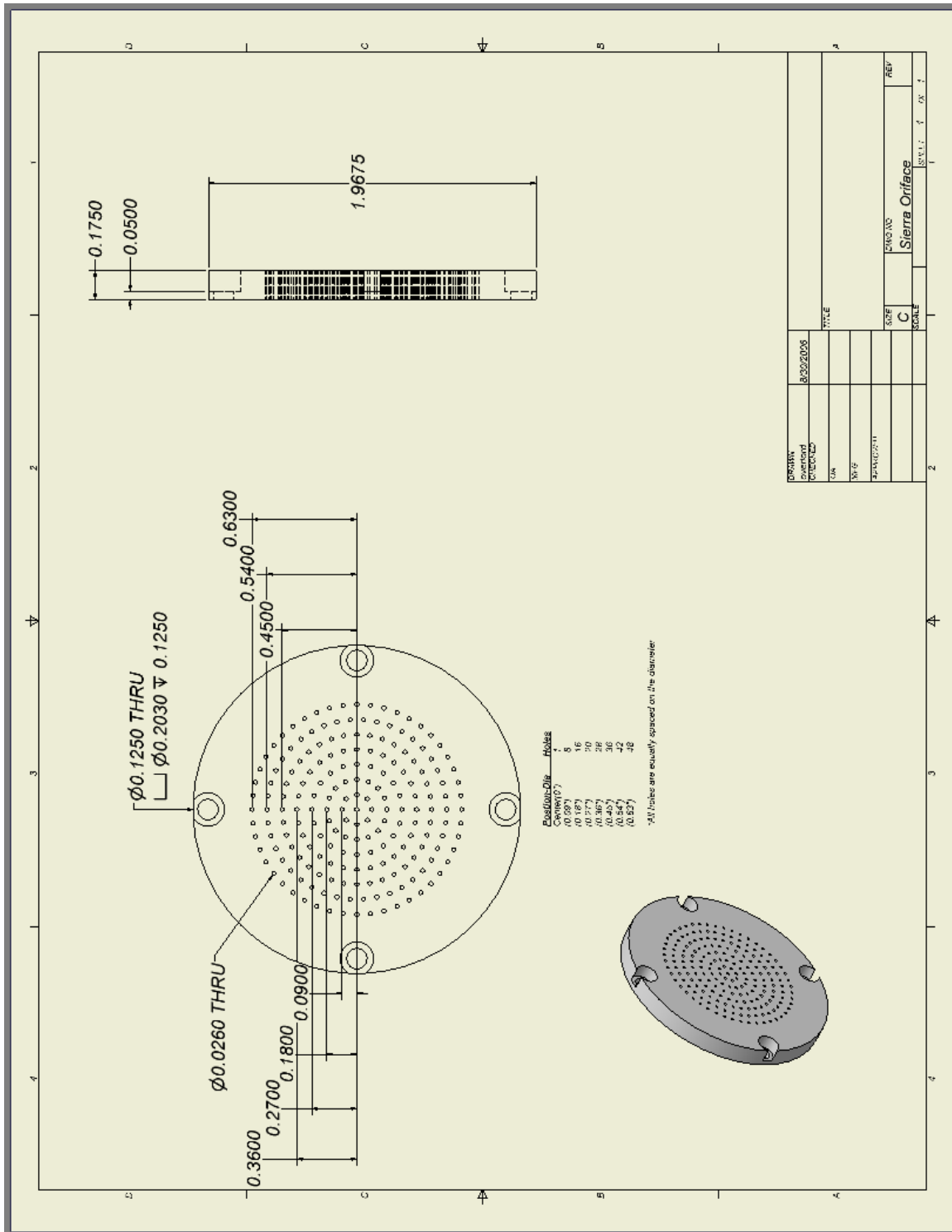


Figure 64. Sierra Engineering Orifice Plate

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## APPENDIX E: CONTROL CODE

### Facility Op Module

```
Private Sub Abort_Click()  
    AbortFlag = True  
    ManualControlPanel.Show  
    iStatus% = DIG_Out_Port(3, 0, 0)  
    iStatus% = DIG_Out_Port(3, 1, 0)  
    iStatus% = DIG_Out_Port(3, 2, 0)  
  
    Timer1.Enabled = False  
    Timer3.Enabled = False  
    'Reset all manual control switches  
    'Close all Ball Valves  
    ManualControlPanel.H2O2SolTorchOn_Click  
    ManualControlPanel.O2BallEngineOn_Click  
    ManualControlPanel.C2H4BallEngineOn_Click  
    ManualControlPanel.H2O2BallTorchOn_Click  
    ManualControlPanel.N2BallPurgeOn_Click  
    ManualControlPanel.O2C2H4BallSupplyOn_Click  
    ManualControlPanel.N2BallSupplyOn_Click  
    ManualControlPanel.N2BallAccOn_Click  
    'Close all Solenoid Valves  
    ManualControlPanel.N2SolVentOn_Click  
    ManualControlPanel.H2SolAccumOn_Click  
    ManualControlPanel.C2H4SolAccumOn_Click  
  
    'Rocket Engine and Torch Off...  
    RocketEngine(1).Visible = False  
    RocketEngine(0).Visible = True  
    'Continue with all lines off...  
    N2Pipe(0).FillColor = &H808080  
    N2Pipe(1).FillColor = &H808080  
    N2Pipe(2).FillColor = &H808080  
    N2Pipe(3).FillColor = &H808080  
    N2Pipe(4).FillColor = &H808080  
    N2Pipe(5).FillColor = &H808080  
    N2Pipe(6).FillColor = &H808080  
    N2Pipe(7).FillColor = &H808080  
    N2Pipe(8).FillColor = &H808080  
    N2Pipe(9).FillColor = &H808080  
    N2Pipe(10).FillColor = &H808080  
    N2Pipe(11).FillColor = &H808080  
    N2Pipe(12).FillColor = &H808080  
    N2Pipe(13).FillColor = &H808080  
    N2Pipe(14).FillColor = &H808080  
  
    O2Pipe(0).FillColor = &H808080  
    O2Pipe(1).FillColor = &H808080  
    O2Pipe(2).FillColor = &H808080  
    O2Pipe(3).FillColor = &H808080  
    O2Pipe(4).FillColor = &H808080  
    O2Pipe(5).FillColor = &H808080  
    O2Pipe(6).FillColor = &H808080  
    O2Pipe(7).FillColor = &H808080  
    O2Pipe(8).FillColor = &H808080  
    O2Pipe(9).FillColor = &H808080  
    O2Pipe(10).FillColor = &H808080  
    O2Pipe(11).FillColor = &H808080  
  
    H2Pipe(0).FillColor = &H808080  
    H2Pipe(1).FillColor = &H808080  
    H2Pipe(2).FillColor = &H808080  
    H2Pipe(3).FillColor = &H808080  
    H2Pipe(4).FillColor = &H808080  
    H2Pipe(5).FillColor = &H808080
```

```

H2Pipe(6).FillColor = &H808080
H2Pipe(7).FillColor = &H808080
H2Pipe(8).FillColor = &H808080
H2Pipe(9).FillColor = &H808080
H2Pipe(10).FillColor = &H808080
H2Pipe(11).FillColor = &H808080

C2H4Pipe(0).FillColor = &H808080
C2H4Pipe(1).FillColor = &H808080
C2H4Pipe(2).FillColor = &H808080
C2H4Pipe(3).FillColor = &H808080
C2H4Pipe(4).FillColor = &H808080
C2H4Pipe(5).FillColor = &H808080
C2H4Pipe(6).FillColor = &H808080
C2H4Pipe(7).FillColor = &H808080
C2H4Pipe(8).FillColor = &H808080
C2H4Pipe(9).FillColor = &H808080
C2H4Pipe(10).FillColor = &H808080
C2H4Pipe(11).FillColor = &H808080

' Save Data to Output File

    StatusBox.Text = "Saving Data to File"
    DoEvents
    EXPNAME = RunConditions.ExpFileName.Text
    OUTNAME = "C:\TC#3_OUTPUT\" + EXPNAME + ".DAT"
    Open OUTNAME For Output As #1
    Print #1, "      Time(s)          N2Pressure(psi)      H2SupplyPressure(psi)
C2H4SupplyPressure(psi)      WaterPressure(psi)      WaterTempChamber(F)      WaterTempNozzle(F)
InjectorTemp(F)          O2Pressure(psi)          O2ManifoldPressure(psi)      C2H4Pressure(psi)
C2H4ManifoldPressure(psi)      ChamberPressure(psi)      Thrust(lbs)      DesiredMassFlowO2(lb/s)
DesiredMassFlowFuel(lb/s)"
    Print #1, " -----"
    -----
    -----
    -----"
    For T = 1 To Tindex

        VAROUT(T, 1) = Format(VAROUT(T, 1), "###.##0")
        VAROUT(T, 2) = Format(VAROUT(T, 2), "#####.##0")
        VAROUT(T, 3) = Format(VAROUT(T, 3), "#####.##0")
        VAROUT(T, 4) = Format(VAROUT(T, 4), "#####.##0")
        VAROUT(T, 5) = Format(VAROUT(T, 5), "#####.##0")
        VAROUT(T, 6) = Format(VAROUT(T, 6), "#####.##0")
        VAROUT(T, 7) = Format(VAROUT(T, 7), "#####.##0")
        VAROUT(T, 8) = Format(VAROUT(T, 8), "#####.##0")
        VAROUT(T, 9) = Format(VAROUT(T, 9), "#####.##0")
        VAROUT(T, 10) = Format(VAROUT(T, 10), "#####.##0")
        VAROUT(T, 11) = Format(VAROUT(T, 11), "#####.##0")
        VAROUT(T, 12) = Format(VAROUT(T, 12), "#####.##0")
        VAROUT(T, 13) = Format(VAROUT(T, 13), "#####.##0")
        VAROUT(T, 14) = Format(VAROUT(T, 14), "#####.##0")
        VAROUT(T, 15) = Format(VAROUT(T, 15), "#####.##0")
        VAROUT(T, 16) = Format(VAROUT(T, 16), "#####.##0")

        Print #1, Tab(4); VAROUT(T, 1); Tab(16); VAROUT(T, 2); Tab(34);
VAROUT(T, 3); Tab(54); VAROUT(T, 4); Tab(78); VAROUT(T, 5); Tab(104); VAROUT(T, 6);
Tab(120); VAROUT(T, 7); Tab(140); VAROUT(T, 8); Tab(158); VAROUT(T, 9); Tab(176);
VAROUT(T, 10); Tab(202); VAROUT(T, 11); Tab(224); VAROUT(T, 12); Tab(246); VAROUT(T, 13);
Tab(268); VAROUT(T, 14); Tab(288); VAROUT(T, 15); Tab(306); VAROUT(T, 16); Tab(326);
'VAROUT(T, 17); Tab(344); VAROUT(T, 18); Tab(364); VAROUT(T, 19); Tab(382); VAROUT(T,
20); Tab(400); VAROUT(T, 21); Tab(418); VAROUT(T, 22);

    Next T
    Close 1

    Label14.Visible = False
    Shape25.Visible = False

    StartRun.Visible = True
    Abort.Visible = False
    StatusBox.Text = "Aborting...Facility Secure."

```

```

End Sub

Private Sub ExitButton_Click()
    RunCondition.SetFocus
End Sub
Private Sub Command2_Click()
    Command2.Visible = False          'PIO Output Channel PA5
    'Light3On.Visible = False
    Command3.Visible = True

    dwDOValueA = dwDOValueA - 32

    iStatus% = DIG_Out_Port(3, 0, dwDOValueA)
End Sub
Private Sub Command3_Click()
    Command3.Visible = False
    Command2.Visible = True
    dwDOValueA = dwDOValueA + 32
    iStatus% = DIG_Out_Port(3, 0, dwDOValueA)

End Sub

Private Sub Calibration_Click()
    Calibrate.Show
End Sub

Private Sub Exit_Click()
    FacilityOp.Hide
    Main.Show
End Sub

Private Sub ManControl_Click()
    ManualControlPanel.Show
End Sub

Private Sub Pressurize_Click()
    Calibrate.Show

    'Open O2/C2H4 Ball Supply
    If ManualControlPanel.O2C2H4BallSupplyOff.Visible = True Then
        ManualControlPanel.O2C2H4BallSupplyOff_Click
        ManualControlPanel.O2C2H4BallSupplyOn.Refresh
    End If
    DoEvents

    'Set O2 Pressure
    StatusBox.Text = "Setting O2 Pressure"
    If Calibrate.Label2.Visible = False Then
        Calibrate.SetO2Pressure_Click
    End If
    DoEvents
    StatusBox.Text = "O2 Pressure is Set"

    'Open N2 Ball Supply
    If ManualControlPanel.N2BallSupplyOff.Visible = True Then
        ManualControlPanel.N2BallSupplyOff_Click
        ManualControlPanel.N2BallSupplyOn.Refresh
    End If
    DoEvents

    'Open N2 Ball Accum
    If ManualControlPanel.N2BallAccOff.Visible = True Then
        ManualControlPanel.N2BallAccOff_Click
        ManualControlPanel.N2BallAccOn.Refresh
    End If
    DoEvents

    'Ensure the N2 Sol vent is closed
    If ManualControlPanel.N2SolVentOn.Visible = True Then
        ManualControlPanel.N2SolVentOn_Click
    End If

```

```

ManualControlPanel.N2SolVentOn.Refresh
End If
DoEvents

'Set Fuel Pressure
StatusBox.Text = "Setting Fuel Pressure"
If Calibrate.Label4.Visible = False Then
    Calibrate.SetFuelPressure_Click
End If
DoEvents
StatusBox.Text = "Fuel Pressure is Set"

'Close O2/C2H4 Ball Supply
If ManualControlPanel.O2C2H4BallSupplyOn.Visible = True Then
    ManualControlPanel.O2C2H4BallSupplyOn_Click
    ManualControlPanel.O2C2H4BallSupplyOff.Refresh
End If

'Close N2 Ball Supply
If ManualControlPanel.N2BallSupplyOn.Visible = True Then
    ManualControlPanel.N2BallSupplyOn_Click
    ManualControlPanel.N2BallSupplyOff.Refresh
End If

'Close N2 Ball Accum
If ManualControlPanel.N2BallAccOn.Visible = True Then
    ManualControlPanel.N2BallAccOn_Click
    ManualControlPanel.N2BallAccOff.Refresh
End If

Calibrate.Hide
End Sub

Private Sub RunCondition_Click()
    RunConditions.Show
End Sub

Private Sub StartRun_Click()
    ManualControlPanel.Show

    'Ensure water pressure is above 15 psi
    If (WaterPressure.Text < 15) Then
        Abort_Click
        StatusBox.Text = "Water Pressure Low...Aborting Run"
        GoTo 11
    End If

    'To Tare the temperature for Injector Temp for flashback and thrust
    InjectorTempTare = InjectorTemp
    ThrustTare = Thrust
    'C2H4Temp variable needs to be relabeled when assembled...done.
    'Need to uncomment the Injector Temp abort criteria
    'Text4.Text = InjectorTempTare
    'Text5.Text = ThrustTare

    AbortFlag = False
    StartRun.Visible = False
    Abort.Visible = True

    ' Get Time Variables From Run Conditions
    IgnitionDelay = RunConditions.IgnitionDelay.Text
    TorchDuration = RunConditions.TorchDuration.Text
    O2Delay = RunConditions.O2Delay.Text
    C2H4Duration = RunConditions.C2H4Duration.Text
    N2Purge = RunConditions.N2PurgeDuration.Text

    ' Open Facility

    StatusBox.Text = "Opening Facility"
    For T = 1 To 150000: DoEvents: Next T
    If AbortFlag = True Then GoTo 10

```

```

StatusBox.Text = "Opening N2,O2, and C2H4 Tank Supply"
If ManualControlPanel.O2C2H4BallSupplyOff.Visible = True Then
    ManualControlPanel.O2C2H4BallSupplyOff_Click
    ManualControlPanel.O2C2H4BallSupplyOff.Refresh
End If
If ManualControlPanel.N2BallSupplyOff.Visible = True Then
    ManualControlPanel.N2BallSupplyOff_Click
    ManualControlPanel.N2BallSupplyOff.Refresh
End If
If ManualControlPanel.N2BallAccOff.Visible = True Then
    ManualControlPanel.N2BallAccOff_Click
    ManualControlPanel.N2BallAccOff.Refresh
End If

For T = 1 To 150000: DoEvents: Next T
If AbortFlag = True Then GoTo 10
StatusBox.Text = "Opening Torch H2/O2 Ball Supply"
If ManualControlPanel.H2O2BallTorchOff.Visible = True Then
    ManualControlPanel.H2O2BallTorchOff_Click
    ManualControlPanel.H2O2BallTorchOff.Refresh
End If

'Pressures are all zero...
' Enable Timer3 and Record Pressures For 1 sec to acquire baseline conditions
Tindex = 0
Timer3.Enabled = True
7 DoEvents
If Tindex > 10 Then
    Timer3.Enabled = False
Else
    GoTo 7
End If

For T = 1 To 90000: DoEvents: Next T
If AbortFlag = True Then GoTo 10
'Check for Valid Pressure Ranges
'Purge O2 Line for Two Seconds
StatusBox.Text = "Opening N2 Purge Line"

If ManualControlPanel.N2BallPurgeOff.Visible = True Then
    ManualControlPanel.N2BallPurgeOff_Click
    ManualControlPanel.N2BallPurgeOff.Refresh
End If

'Close Purge valve

'Cold Flow Testing
For T = 1 To 200000: DoEvents: Next T
ManualControlPanel.N2BallPurgeOn_Click
ManualControlPanel.N2BallPurgeOn.Refresh

StatusBox.Text = "Preparing to Run..."
'Wait 2 seconds
For T = 1 To 500000: DoEvents: Next T
If AbortFlag = True Then GoTo 10
StatusBox.Text = "Running..."
' Enable Timer3 and Record Pressures
Timer3.Enabled = True
' Send Trigger to AGEMA and INSTASPEC
DoEvents
iStatus% = AO_VWrite(1, 0, 5)
iStatus% = AO_VWrite(1, 1, 5)
GetTime
StartTime = CurrentTime
Timer1.Enabled = True
GoTo 11
10 StatusBox.Text = "Facility Secure...Run Complete"
iStatus% = DIG_Out_Port(3, 0, 0)
iStatus% = DIG_Out_Port(3, 1, 0)
iStatus% = DIG_Out_Port(3, 2, 0)
iStatus% = AO_VWrite(1, 1, 5)

```

```

        Timer1.Enabled = False
        Timer3.Enabled = False
11 'End of StartRun
End Sub

Function GetTime()
    TenthsCount = TenthsCount + 1
    CurrentTime = Hour(Time) * 60 * 60 + Minute(Time) * 60 + Second(Time)
    If Second(Time) <> OldSec Then TenthsCount = 0
    OldSec = Second(Time)
    CurrentTime = CurrentTime + TenthsCount * 0.1
End Function

Private Sub Timer1_Timer()
    'Controls Event Sequence
    GetTime
    If CurrentTime = StartTime + 2 Then
        'Fuel On
        ManualControlPanel.C2H4BallEngineOff_Click
        ManualControlPanel.C2H4BallEngineOff.Refresh
        'This is turning on N2 as dilutant
        ManualControlPanel.N2BallPurgeOff_Click
        ManualControlPanel.N2BallPurgeOff.Refresh
    End If

    If CurrentTime = StartTime + 2 + O2Delay Then
        'O2 On
        ManualControlPanel.O2BallEngineOff_Click
        ManualControlPanel.O2BallEngineOff.Refresh
    End If

    If CurrentTime = StartTime + 2 + IgnitionDelay Then
        'Torch On
        ManualControlPanel.H2O2SolTorchOff_Click
        ManualControlPanel.H2O2SolTorchOff.Refresh
    End If
    If CurrentTime = StartTime + 2 + IgnitionDelay + TorchDuration Then
        'Torch Off
        ManualControlPanel.H2O2SolTorchOn_Click
        ManualControlPanel.H2O2SolTorchOn.Refresh
        'This is turning off N2 as dilutant
        ManualControlPanel.N2BallPurgeOn_Click
        ManualControlPanel.N2BallPurgeOn.Refresh
    End If
    RocketEngine(1).Visible = True
    RocketEngine(0).Visible = False

    'Oxygen takes 3 seconds to close
    If CurrentTime = StartTime + 2 + C2H4Duration Then
        'O2 Off/Fuel Off/N2 Purge On
        ManualControlPanel.C2H4BallEngineOn_Click
        ManualControlPanel.C2H4BallEngineOn.Refresh
        ManualControlPanel.O2BallEngineOn_Click
        ManualControlPanel.O2BallEngineOn.Refresh
        ManualControlPanel.N2BallPurgeOff_Click
        ManualControlPanel.N2BallPurgeOff.Refresh
        DoEvents
    End If

    If CurrentTime = StartTime + 2 + C2H4Duration + N2Purge Then
        ManualControlPanel.N2BallPurgeOn_Click
        ManualControlPanel.N2BallPurgeOn.Refresh
        GoTo 23
    End If
    GoTo 25
23    Timer1.Enabled = False
        RocketEngine(0).Visible = True
        RocketEngine(1).Visible = False

        StatusBox.Text = "Run Complete...!"
    For T = 1 To 100000: DoEvents: Next T

```

```

        StatusBox.Text = "Securing Facility..."
        'Close N2/O2/C2H4 Supply Gases
        ManualControlPanel.O2C2H4BallSupplyOn_Click
        ManualControlPanel.O2C2H4BallSupplyOn.Refresh
        ManualControlPanel.N2BallSupplyOn_Click
    For T = 1 To 40000: DoEvents: Next T
        'Close H2/O2 Torch Supply Gases
        ManualControlPanel.H2O2BallTorchOn_Click
        ManualControlPanel.H2O2BallTorchOn.Refresh
    For T = 1 To 40000: DoEvents: Next T
        'Close N2 Accumulator Isolation
        ManualControlPanel.N2BallAccOn_Click
        ManualControlPanel.N2BallAccOn.Refresh
    For T = 1 To 40000: DoEvents: Next T
        StatusBox.Text = "Facility Secure."
        iStatus% = DIG_Out_Port(3, 0, 0)
        iStatus% = DIG_Out_Port(3, 1, 0)
        iStatus% = DIG_Out_Port(3, 2, 0)
        Timer3.Enabled = False
        Turn off Trigger
        iStatus% = AO_VWrite(1, 0, 0)
        iStatus% = AO_VWrite(1, 1, 5)
    '
    ' Save Data to Output File

        StatusBox.Text = "Saving Data to File"
        DoEvents
        EXPNAME = RunConditions.ExpFileName.Text
        OUTNAME = "C:\TC#3_OUTPUT\" + EXPNAME + ".DAT"
        Open OUTNAME For Output As #1
        Print #1, " Time(s) N2Pressure(psi) H2SupplyPressure(psi)
C2H4SupplyPressure(psi) WaterPressure(psi) WaterTempChamber(F) WaterTempNozzle(F)
InjectorTemp(F) O2Pressure(psi) O2ManifoldPressure(psi) C2H4Pressure(psi)
C2H4ManifoldPressure(psi) ChamberPressure(psi) Thrust(lbs) DesiredMassFlowO2(lb/s)
DesiredMassFlowFuel(lb/s)"
        Print #1, " -----
-----
-----
-----"

        For T = 1 To Tindex

            VAROUT(T, 1) = Format(VAROUT(T, 1), "##.#0")
            VAROUT(T, 2) = Format(VAROUT(T, 2), "####.#0")
            VAROUT(T, 3) = Format(VAROUT(T, 3), "####.#0")
            VAROUT(T, 4) = Format(VAROUT(T, 4), "####.#0")
            VAROUT(T, 5) = Format(VAROUT(T, 5), "####.#0")
            VAROUT(T, 6) = Format(VAROUT(T, 6), "####.#0")
            VAROUT(T, 7) = Format(VAROUT(T, 7), "####.#0")
            VAROUT(T, 8) = Format(VAROUT(T, 8), "####.#0")
            VAROUT(T, 9) = Format(VAROUT(T, 9), "####.#0")
            VAROUT(T, 10) = Format(VAROUT(T, 10), "####.#0")
            VAROUT(T, 11) = Format(VAROUT(T, 11), "####.#0")
            VAROUT(T, 12) = Format(VAROUT(T, 12), "####.#0")
            VAROUT(T, 13) = Format(VAROUT(T, 13), "####.#0")
            VAROUT(T, 14) = Format(VAROUT(T, 14), "####.#0")
            VAROUT(T, 15) = Format(VAROUT(T, 15), "#.####0")
            VAROUT(T, 16) = Format(VAROUT(T, 16), "#.####0")
            'VAROUT(T, 17) = Format(VAROUT(T, 17), "####.#0")
            'VAROUT(T, 18) = Format(VAROUT(T, 18), "####.#0")
            'VAROUT(T, 19) = Format(VAROUT(T, 19), "####.#0")
            'VAROUT(T, 20) = Format(VAROUT(T, 20), "####.#0")
            'VAROUT(T, 21) = Format(VAROUT(T, 21), "#.#0")
            'VAROUT(T, 22) = Format(VAROUT(T, 22), "#.##0")

            Print #1, Tab(4); VAROUT(T, 1); Tab(16); VAROUT(T, 2); Tab(34);
VAROUT(T, 3); Tab(54); VAROUT(T, 4); Tab(78); VAROUT(T, 5); Tab(104); VAROUT(T, 6);
Tab(120); VAROUT(T, 7); Tab(140); VAROUT(T, 8); Tab(158); VAROUT(T, 9); Tab(176);
VAROUT(T, 10); Tab(202); VAROUT(T, 11); Tab(224); VAROUT(T, 12); Tab(246); VAROUT(T, 13);
Tab(268); VAROUT(T, 14); Tab(288); VAROUT(T, 15); Tab(306); VAROUT(T, 16); Tab(326);
'VAROUT(T, 17); Tab(344); VAROUT(T, 18); Tab(364); VAROUT(T, 19); Tab(174); VAROUT(T,
20); Tab(184); VAROUT(T, 21); Tab(184); VAROUT(T, 22);

```

```

        Next T
        Close 1
        StartRun.Visible = True
        Abort.Visible = False
        Label14.Visible = False
        Shape25.Visible = False

        StatusBox.Text = "Facility Secure."
        Timer1.Enabled = False
25      'Loop

End Sub

Private Sub Timer2_Timer()
    'Check all line and combustor Pressures
    'change loop to 12
    For k = 0 To 15
        iStatus% = AI_VRead(1, k, 1, Volts(k))
    Next k
    'Calculate Line Pressures
    N2Pressure = Volts(0) * 750 - 750 '3000 psi cald DD
    C2H4ManifoldPressure = Volts(1) * 245.248 - 251.38 'precision cald DD
    ChamberPressure = Volts(2) * 244.539 - 255.787 'precision cald DD
    C2H4Pressure = Volts(3) * 245.27 - 253.854 'precision cald DD
    C2H4SupplyPressure = Volts(4) * 756.62 - 783.1 'cal DD
    H2SupplyPress = Volts(5) * 448.43 - 242.152 'cald DD
    O2ManifoldPressure = Volts(6) * 254.528 - 251.665 'precision cald DD
    N2SupplyPressure = Volts(7) * 754.907 - 774.534 'cald DD
    O2Pressure = Volts(8) * 207.285 - 37.311 ' NOT precision cald DD
    Thrust = (Volts(9) * 108.863 - 14.765) - ThrustTare 'precision cald
    DD...changes when detached
    WaterPressure = Volts(10) * 101.01 - 105.051 'cald DD
    FuelFilmSet = Volts(11) * 753.769 - 768.844 'cald DD
    O2SupplyPressure = Volts(12) * 611 - 53
    'Check Spool Temperatures and Heat Transfer Numbers
    iStatus% = AI_VRead(2, 0, 1, Volts(0))
    iStatus% = AI_VRead(2, 1, 1, Volts(1))
    iStatus% = AI_VRead(2, 2, 1, Volts(2))
    iStatus% = AI_VRead(2, 3, 1, Volts(3))
    InjectorTemp = Volts(0) * 73.075 - 67.912 'NOT precision cald DD
    Temp2 = "N/A" ' Volts(1) * 50
    WaterTempChamber = Volts(2) * 40 - 0
    WaterTempNozzle = Volts(3) * 49.73 - 43.71

    'Test values
    'O2Pressure = 15
    'N2Pressure = 16
    'N2SupplyPressure = 15
    'H2SupplyPress = 15
    'O2SupplyPressure = 160
    'C2H4SupplyPressure = 15
    'C2H4Pressure = 15
    '***UnComment WaterPressure for START RUN tests
    'WaterPressure = 18
    'ChamberPressure = 15
    'InjectorTemp = 85

    'Update line colors
    If N2SupplyPressure > 10 Then
        N2Pipe(0).FillColor = &HFF0000
        N2Pipe(1).FillColor = &HFF0000
        N2Pipe(2).FillColor = &HFF0000
        N2Pipe(9).FillColor = &HFF0000
        N2Pipe(10).FillColor = &HFF0000
        N2Pipe(11).FillColor = &HFF0000
        If ManualControlPanel.N2BallSupplyOn.Visible = True Then
            N2Pipe(3).FillColor = &HFF0000
            N2Pipe(4).FillColor = &HFF0000
            If ManualControlPanel.N2BallAccOn.Visible = True Then
                N2Pipe(5).FillColor = &HFF0000
                N2Pipe(6).FillColor = &HFF0000
            End If
        End If
    End If
End Sub

```



```

        N2Pipe(7).FillColor = &HFF0000
        If ManualControlPanel.N2SolVentOn.Visible = True Then
            N2Pipe(8).FillColor = &HFF0000
        End If
    End If
End If
If ManualControlPanel.N2BallPurgeOn.Visible = True Then
    N2Pipe(12).FillColor = &HFF0000
    N2Pipe(13).FillColor = &HFF0000
    N2Pipe(14).FillColor = &HFF0000
    O2Pipe(10).FillColor = &HFF0000
    O2Pipe(11).FillColor = &HFF0000
End If
Else
    N2SupplyPressure = 0
End If

If N2Pressure < 10 Then
    N2Pressure = 0
End If

If H2SupplyPress > 10 Then
    H2Pipe(0).FillColor = &HFF&
    H2Pipe(1).FillColor = &HFF&
    H2Pipe(2).FillColor = &HFF&
    H2Pipe(3).FillColor = &HFF&
    H2Pipe(4).FillColor = &HFF&
    H2Pipe(6).FillColor = &HFF&
    H2Pipe(7).FillColor = &HFF&
    If ManualControlPanel.H2SolAccumOn.Visible = True Then
        H2Pipe(5).FillColor = &HFF&
        H2Pipe(8).FillColor = &HFF&
    End If
    If ManualControlPanel.H2O2BallTorchOn.Visible = True Then
        H2Pipe(9).FillColor = &HFF&
    End If
    If ManualControlPanel.H2O2SolTorchOn.Visible = True Then
        H2Pipe(10).FillColor = &HFF&
        H2Pipe(11).FillColor = &HFF&
    End If
Else
    H2SupplyPress = 0
End If

If O2SupplyPressure > 10 Then
    O2Pipe(0).FillColor = &HFF00&
    O2Pipe(1).FillColor = &HFF00&
    O2Pipe(2).FillColor = &HFF00&
    If ManualControlPanel.O2C2H4BallSupplyOn.Visible = True Then
        O2Pipe(3).FillColor = &HFF00&
        O2Pipe(4).FillColor = &HFF00&
        O2Pipe(7).FillColor = &HFF00&
        O2Pipe(8).FillColor = &HFF00&
        If ManualControlPanel.O2BallEngineOn.Visible = True Then
            O2Pipe(9).FillColor = &HFF00&
            O2Pipe(10).FillColor = &HFF00&
            O2Pipe(11).FillColor = &HFF00&
        End If
        If ManualControlPanel.H2O2BallTorchOn.Visible = True Then
            O2Pipe(5).FillColor = &HFF00&
        End If
        If ManualControlPanel.H2O2SolTorchOn.Visible = True Then
            O2Pipe(6).FillColor = &HFF00&
        End If
    End If
Else
    O2SupplyPressure = 0
End If

If O2Pressure < 15 Then

```

```

        O2Pressure = 0
    End If

    If C2H4SupplyPressure > 10 Then
        C2H4Pipe(0).FillColor = &HFFFF00
        C2H4Pipe(1).FillColor = &HFFFF00
        If ManualControlPanel.O2C2H4BallSupplyOn.Visible = True Then
            C2H4Pipe(2).FillColor = &HFFFF00
            C2H4Pipe(3).FillColor = &HFFFF00
            If ManualControlPanel.C2H4SolAccumOn.Visible = True Then
                C2H4Pipe(4).FillColor = &HFFFF00
            End If
        End If
    Else
        C2H4SupplyPressure = 0
    End If

    If C2H4Pressure > 10 Then
        C2H4Pipe(5).FillColor = &HFFFF00
        C2H4Pipe(6).FillColor = &HFFFF00
        C2H4Pipe(7).FillColor = &HFFFF00
        C2H4Pipe(8).FillColor = &HFFFF00
        If ManualControlPanel.C2H4BallEngineOn.Visible = True Then
            C2H4Pipe(9).FillColor = &HFFFF00
            C2H4Pipe(10).FillColor = &HFFFF00
            C2H4Pipe(11).FillColor = &HFFFF00
        End If
    Else
        C2H4Pressure = 0
    End If

    If WaterPressure > 5 Then
        WaterPipe(0).FillColor = &HC00000
        WaterPipe(1).FillColor = &HC00000
        WaterPipe(2).FillColor = &HC00000
        WaterPipe(3).FillColor = &HC00000
    Else
        WaterPressure = 0
    End If

    If ChamberPressure < 10 Then
        ChamberPressure = 0
    End If

    If O2ManifoldPressure < 10 Then
        O2ManifoldPressure = 0
    End If

    If C2H4ManifoldPressure < 10 Then
        C2H4ManifoldPressure = 0
    End If

    PowerMeter = Format(PowerMeter, "#.##")
    ChamberPressure = Format(ChamberPressure, "###.0")
    C2H4Pressure.Text = Format(C2H4Pressure, "#####.0")
    N2Pressure.Text = Format(N2Pressure, "#####.0")
    C2H4SupplyPressure.Text = Format(C2H4SupplyPressure, "#####.0")
    C2H4ManifoldPressure.Text = Format(C2H4ManifoldPressure, "###.0")
    H2SupplyPressure(0).Text = Format(H2SupplyPress, "#####.0")
    H2SupplyPressure(1).Text = Format(H2SupplyPress, "#####.0")
    O2Pressure.Text = Format(O2Pressure, "###.0")
    O2SupplyPressure.Text = Format(O2SupplyPressure, "###.0")
    O2ManifoldPressure.Text = Format(O2ManifoldPressure, "###.0")
    N2SupplyPressure.Text = Format(N2SupplyPressure, "#####.0")
    WaterPressure.Text = Format(WaterPressure, "###.##")
    WaterTempNozzle.Text = Format(WaterTempNozzle, "###.0")
    WaterTempChamber.Text = Format(WaterTempChamber, "###.0")
    'C2H4Temp.Text = Format(C2H4Temp, "###.0")
    InjectorTemp.Text = Format(InjectorTemp, "###.0")
    Thrust = Format(Thrust, "###.0")

```

```

Text1.Text = dwDOValueA
Text2.Text = dwDOValueB
Text3.Text = dwDOValueC

' *****
' Update Annotator
' *****
MSComm1.Output = Chr$(27) + "H"
MSComm1.Output = "Title: " + RunConditions.ExpFileName.Text + Chr$(10) +
Chr$(13)
MSComm1.Output = "Pcham: " + Str(ChamberPressure) + " " + Chr$(10) +
Chr$(13)
MSComm1.Output = "Thrust: " + Str(Thrust) + " " + Chr$(13)
End Sub

Private Sub Timer3_Timer()
' Trigger Instaspec Scan
iStatus% = AO_VWrite(2, 0, 5)
' Record Pressures and Voltages at 10 Hz
For k = 0 To 15
iStatus% = AI_VRead(1, k, 1, Volts(k))
Next k

' Calculate Line Pressures
'This is copied...changes done in timer 2
'Calculate Line Pressures
N2Pressure = Volts(0) * 750 - 750 '3000 psi cald DD
C2H4ManifoldPressure = Volts(1) * 245.248 - 251.38 'precision cald DD
ChamberPressure = Volts(2) * 244.539 - 255.787 'precision cald DD
C2H4Pressure = Volts(3) * 245.27 - 253.854 'precision cald DD
C2H4SupplyPressure = Volts(4) * 756.62 - 783.1 'cald DD
H2SupplyPress = Volts(5) * 448.43 - 242.152 'cald DD
O2ManifoldPressure = Volts(6) * 254.528 - 251.665 'precision cald DD
N2SupplyPressure = Volts(7) * 754.907 - 774.534 'cald DD
O2Pressure = Volts(8) * 207.285 - 37.311 'precision cald DD
Thrust = (Volts(9) * 108.863 - 14.765) - ThrustTare 'precision cald
DD...changes when detached
'***Comment out WaterPressure for START RUN tests
WaterPressure = Volts(10) * 101.01 - 105.051 'cald DD
FuelFilmSet = Volts(11) * 753.769 - 768.844 'cald DD
O2SupplyPressure = Volts(12) * 611 - 53
'Check Spool Temperatures and Heat Transfer Numbers
iStatus% = AI_VRead(2, 0, 1, Volts(0))
iStatus% = AI_VRead(2, 1, 1, Volts(1))
iStatus% = AI_VRead(2, 2, 1, Volts(2))
iStatus% = AI_VRead(2, 3, 1, Volts(3))
iStatus% = AI_VRead(2, 4, 1, Volts(4))
iStatus% = AI_VRead(2, 5, 1, Volts(5))
'C2H4Temp = Volts(0) * 53.4 - 23.24
InjectorTemp = Volts(0) * 73.075 - 67.912 'NOT precision cald DD use good
amplifier
Temp2 = Volts(1)
WaterTempChamber = Volts(2) * 40 - 0
WaterTempNozzle = Volts(3) * 49.73 - 43.71
VAROUT(Tindex, 1) = (Tindex - 1) * 0.1
VAROUT(Tindex, 2) = N2Pressure
VAROUT(Tindex, 3) = H2SupplyPress
VAROUT(Tindex, 4) = C2H4SupplyPressure
VAROUT(Tindex, 5) = WaterPressure
VAROUT(Tindex, 6) = WaterTempChamber
VAROUT(Tindex, 7) = WaterTempNozzle
VAROUT(Tindex, 8) = InjectorTemp
VAROUT(Tindex, 9) = O2Pressure
VAROUT(Tindex, 10) = O2ManifoldPressure
VAROUT(Tindex, 11) = C2H4Pressure
VAROUT(Tindex, 12) = C2H4ManifoldPressure
VAROUT(Tindex, 13) = ChamberPressure
VAROUT(Tindex, 14) = Thrust
VAROUT(Tindex, 15) = RunConditions.DesiredMassFlowO2.Text
VAROUT(Tindex, 16) = RunConditions.DesiredMassFlowFuel.Text

```

```

Tindex = Tindex + 1
' Reset Instaspec Trigger to 0
iStatus% = AO_VWrite(2, 0, 0)
'
' Check for Shutdown Criteria
'Comment for running Non premixed engine
'If InjectorTemp > (InjectorTempTare + 2) Then Abort_Click
If ChamberPressure > 550 Then Abort_Click
'If C2H4Temp > 2000 Then Abort_Click
If WaterTempChamber > 150 Then Abort_Click
If WaterTempNozzle > 150 Then Abort_Click
If WaterPressure < 15 Then Abort_Click
' End If
End Sub

```

## Run Conditions Module

```

Private Sub Exit_Click()
    FacilityOp.MSComm1.Output = Chr$(27) + "H"
    For T = 1 To 3
        FacilityOp.MSComm1.Output = "
    Next T
    RunConditions.Hide

    'Compute Required O2 and Fuel Pressures
    If RunConditions.Option1.Value = True Then
        FacilityOp.DesiredMassFlowO2.Text = RunConditions.DesiredMassFlowO2
        FacilityOp.DesiredMassFlowFuel.Text = RunConditions.DesiredMassFlowFuel
        FacilityOp.DesiredOF.Text = "NA"
        FacilityOp.ExpectedPressure.Text = "NA"

        'Change the Choke Diameter and K value based on fluid
        'O2 Chokes
        If RunConditions.Option10.Value = True Then '0.067"
            ChokeArea = (3.1415 * 0.25) * (0.067 / 39.3701) ^ 2 'm^2
            DesiredO2Pressure = ((DesiredMassFlowO2 / 2.205) * 285# ^ 0.5) /
(ChokeArea * 1 * 0.042405619 * 6894.757) 'psi
        End If

        If RunConditions.Option9.Value = True Then '0.072"
            ChokeArea = (3.1415 * 0.25) * (0.072 / 39.3701) ^ 2 'm^2
            DesiredO2Pressure = ((DesiredMassFlowO2 / 2.205) * 285# ^ 0.5) /
(ChokeArea * 1 * 0.042405619 * 6894.757) 'psi
        End If

        'Fuel Chokes
        If RunConditions.Option6.Value = True Then '0.090"
            ChokeArea = (3.1415 * 0.25) * (0.09 / 39.3701) ^ 2 'm^2
            DesiredFuelPressure = ((DesiredMassFlowFuel / 2.205) * 285# ^ 0.5) /
(ChokeArea * 1 * 0.03808302 * 6894.757) 'psi
        End If

        If RunConditions.Option7.Value = True Then '0.062"
            ChokeArea = (3.1415 * 0.25) * (0.062 / 39.3701) ^ 2 'm^2
            DesiredFuelPressure = ((DesiredMassFlowFuel / 2.205) * 285# ^ 0.5) /
(ChokeArea * 1 * 0.03808302 * 6894.757) 'psi
        End If

        If RunConditions.Option14.Value = True Then '0.067"
            ChokeArea = (3.1415 * 0.25) * (0.067 / 39.3701) ^ 2 'm^2
            DesiredFuelPressure = ((DesiredMassFlowFuel / 2.205) * 285# ^ 0.5) /
(ChokeArea * 1 * 0.03808302 * 6894.757) 'psi
        End If
    End If

    If RunConditions.Option2.Value = True Then
        FacilityOp.DesiredOF.Text = RunConditions.DesiredOF
        FacilityOp.ExpectedPressure.Text = RunConditions.DesiredPressure
        FacilityOp.DesiredMassFlowO2.Text = "NA"
        FacilityOp.DesiredMassFlowFuel.Text = "NA"

        ChamberPressureDesired = RunConditions.DesiredPressure.Text
        DesiredOF = RunConditions.DesiredOF.Text
        If RunConditions.Option18.Value = True Then '.300" throat
            ThroatDiameter = 0.3
        End If

        cstar = (1.417 * DesiredOF ^ 7 - 24.303 * DesiredOF ^ 6 + 159.531 *
DesiredOF ^ 5 - 493.752 * DesiredOF ^ 4 + 725.358 * DesiredOF ^ 3 - 589.652 * DesiredOF ^
2 + 741.193 * DesiredOF + 1120.526) ' m/s

        'cstar = (-0.341 * DesiredOF ^ 7 + 10.415 * DesiredOF ^ 6 - 126.923 *
DesiredOF ^ 5 + 778.486 * DesiredOF ^ 4 - 2444.95 * DesiredOF ^ 3 + 3282.447 * DesiredOF
^ 2 - 191.216 * DesiredOF + 3890.376) * 0.3048 ' m/s

```

```

        ThroatArea = (3.1415 * ThroatDiameter ^ 2 / 4) * 0.00064516 ' m2
        ChamberPressureDesired = ChamberPressureDesired / 14.7 * 101325 ' N/m2

        MdotRequired = (ChamberPressureDesired * ThroatArea) / cstar ' kg/s

        MdotRequiredFuel = MdotRequired / (DesiredOF + 1) ' kg/s
        MdotRequiredO2 = (MdotRequired - MdotRequiredFuel) 'kg/s

        'Change the Choke Diameter and K value based on fluid
        'O2 Chokes
        If RunConditions.Option10.Value = True Then '0.067"
            ChokeArea = (3.1415 * 0.25) * (0.067 / 39.3701) ^ 2 'm^2
            DesiredO2Pressure = (MdotRequiredO2 * 285# ^ 0.5) / (ChokeArea * 1 *
0.042405619 * 6894.757) 'psi
        End If

        If RunConditions.Option9.Value = True Then '0.072"
            ChokeArea = (3.1415 * 0.25) * (0.072 / 39.3701) ^ 2 'm^2
            DesiredO2Pressure = (MdotRequiredO2 * 285# ^ 0.5) / (ChokeArea * 1 *
0.042405619 * 6894.757) 'psi
        End If

        'Fuel Chokes
        If RunConditions.Option6.Value = True Then '0.090"
            ChokeArea = (3.1415 * 0.25) * (0.09 / 39.3701) ^ 2 'm^2
            DesiredFuelPressure = (MdotRequiredFuel * 285# ^ 0.5) / (ChokeArea * 1
* 0.03808302 * 6894.757) 'psi
        End If

        If RunConditions.Option14.Value = True Then '0.067"
            ChokeArea = (3.1415 * 0.25) * (0.067 / 39.3701) ^ 2 'm^2
            DesiredFuelPressure = (MdotRequiredFuel * 285# ^ 0.5) / (ChokeArea * 1
* 0.03808302 * 6894.757) 'psi
        End If

        If RunConditions.Option7.Value = True Then '0.062"
            ChokeArea = (3.1415 * 0.25) * (0.062 / 39.3701) ^ 2 'm^2
            DesiredFuelPressure = (MdotRequiredFuel * 285# ^ 0.5) / (ChokeArea * 1
* 0.03808302 * 6894.757) 'psi
        End If

    End If

    FacilityOp.CalcO2Pressure.Text = Int(DesiredO2Pressure)
    FacilityOp.CalcFuelPressure.Text = Int(DesiredFuelPressure)
    Calibrate.DesiredFuelPressure.Text = Int(DesiredFuelPressure)
    Calibrate.DesiredO2Pressure.Text = Int(DesiredO2Pressure)

End Sub

Private Sub Option18_Click()
    ThroatDia = 0.3
End Sub

Private Sub FuelH2C2H4_Click()
    PercentH2.Enabled = True
    m1 = 36225 * (1 - PercentH2.Text / 100) + (PercentH2.Text / 100) * 34614
    m2 = 22193 * (1 - PercentH2.Text / 100) + (PercentH2.Text / 100) * 21209
    m3 = 48412 * (1 - PercentH2.Text / 100) + (PercentH2.Text / 100) * 46265
    b1 = 876.68 * (1 - PercentH2.Text / 100) + (PercentH2.Text / 100) * 874.09
    b2 = 655.17
    b3 = 770.24
End Sub

Private Sub IgnitionDelay_Change()
    If (IgnitionDelay > 7) Or (IgnitionDelay < 0) Then
        Response = MsgBox("Value Must Be Between 0 and 7", vbOKOnly, "Invalid
Value")
        IgnitionDelay = VScroll11.Value
    End If
End Sub

```

```

        End If
        VScroll11.Value = IgnitionDelay
    End Sub

    Private Sub Text11_Change()
        If IsNumeric(Text11.Text) = True Then
            Shape6.Left = 1440 + O2Delay * 450 + Text11.Text * 450
            Shape6.Width = (Text12.Text - Text11.Text) * 450
        End If
    End Sub

    Private Sub Text12_Change()
        If IsNumeric(Text12.Text) = True Then
            Shape6.Left = 1440 + O2Delay * 450 + Text11.Text * 450
            Shape6.Width = (Text12.Text - Text11.Text) * 450
        End If
    End Sub

    Private Sub TorchDuration_Change()
        If (TorchDuration > 4) Or (TorchDuration < 0) Then
            Response = MsgBox("Value Must Be Between 0 and 4", vbOKOnly, "Invalid
Value")
            TorchDuration = VScroll12.Value
        End If
        VScroll12.Value = TorchDuration
    End Sub

    Private Sub C2H4Duration_Change()
        If (C2H4Duration > 35) Or (C2H4Duration < 0) Then
            Response = MsgBox("Value Must Be Between 0 and 35", vbOKOnly, "Invalid
Value")
            C2H4Duration = VScroll13.Value
        End If
        VScroll13.Value = C2H4Duration
        Shape6.Left = 1440 + O2Delay * 450 + Text11.Text * 450
        Shape6.Width = (Text12.Text - Text11.Text) * 450
    End Sub

    Private Sub O2Delay_Change()
        If (O2Delay > 5) Or (O2Delay < 0) Then
            Response = MsgBox("Value Must Be Between 0 and 5", vbOKOnly, "Invalid
Value")
            O2Delay = VScroll14.Value
        End If
        VScroll14.Value = O2Delay
        Shape6.Left = 1440 + O2Delay * 450 + Text11.Text * 450
        Shape6.Width = (Text12.Text - Text11.Text) * 450
    End Sub

    Private Sub N2PurgeDuration_Change()
        If (N2PurgeDuration > 5) Or (N2PurgeDuration < 0) Then
            Response = MsgBox("Value Must Be Between 0 and 3", vbOKOnly, "Invalid
Value")
            N2PurgeDuration = VScroll15.Value
        End If
        VScroll15.Value = N2PurgeDuration
    End Sub

    Private Sub Text9_Change()
        If IsNumeric(Text9.Text) = True Then
            If Text9.Text < 0 Then Text9.Text = 0
            Shape5.Width = 450 * Text9.Text
            Shape5.Left = Shape2.Left + Shape2.Width - 450 * Text9.Text
        End If
    End Sub

    Private Sub VScroll11_Change()
        IgnitionDelay = VScroll11.Value
        Shape4.Left = 1440 + 450 * IgnitionDelay
    End Sub

```

```

End Sub

Private Sub VScroll2_Change()
    TorchDuration = VScroll2.Value
    Shape4.Width = 450 * TorchDuration
End Sub

Private Sub VScroll3_Change()
    C2H4Duration = VScroll3.Value
    If C2H4Duration < O2Delay Then O2Delay = C2H4Duration
    Shape2.Width = 450 * C2H4Duration
    Shape1.Width = (C2H4Duration - O2Delay) * 450
    Shape3.Left = Shape2.Left + Shape2.Width
End Sub

Private Sub VScroll4_Change()
    O2Delay = VScroll4.Value
    Shape1.Width = (C2H4Duration - O2Delay) * 450
    Shape1.Left = 1440 + O2Delay * 450
    Shape3.Left = Shape2.Left + Shape2.Width
End Sub

Private Sub VScroll5_Change()
    N2PurgeDuration = VScroll5.Value
    Shape3.Width = N2PurgeDuration * 450
End Sub

```



## LIST OF REFERENCES

1. Palmer, Scott M, Johnson, Curtis W., and Stout, Perry W., “PERCORP Enhancement for Improved Soot Modeling,” NASA Phase II SBIR Contract FA9101-04-C-0038, Sierra Engineering Inc., Carson City, NV, August 2006.
2. Glassman, I., *Combustion*, Second Edition, Academic Press, Inc., 1987.
3. Kuo, K.K., *Principles of Combustion*, Second Edition, John Wiley and Sons, 2005.
4. Lewis, B. and von Elbe, G., *Combustion, Flames, and Explosions of Gases*, Academic, 1987.
5. Knuth, William H., Gramer, Daniel J., and St. Clair, Christopher P., “Premixing Rocket Engine Injectors for High Pressure Gaseous Oxygen and Hydrogen,” AIAA Paper 1999-2491, Joint Propulsion Conference and Exhibit, Los Angeles, CA, 20-24 June 1999.
6. Stowe, Albert, “Study of Soot using Mie Scattering Theory for Gaseous Rocket Engines.” Master’s Thesis, Naval Postgraduate School, Monterey, CA, March 2007.
7. Sutton, George P., and Biblarz, Oscar, *Rocket Propulsion Elements*, Seventh Edition, John Wiley and Sons, Inc., 2001.
8. Simmons, Frederick S, *Rocket Exhaust Plume Phenomenology*, The Aerospace Press, 2000.

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